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Geotechnical Stabilisation of Expansive Black Cotton Soil Using Fly Ash and Lime Sludge: Swell-Shrink Behaviour, Strength Development and Microstructural Evaluation

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Abstract

Expansive black cotton soils, covering approximately 20% of India's land area and predominant across Maharashtra, Madhya Pradesh, Karnataka, and parts of Telangana, present a persistent geotechnical challenge for highway embankments, foundations, and canal linings due to their high swell-shrink potential under seasonal moisture variation. Chemical stabilisation using lime is an established remediation technique, but the carbon footprint and cost of conventional hydrated lime have motivated investigation of industrial by-products — fly ash from thermal power generation and lime sludge from paper and sugar industry effluent treatment — as partial or complete substitutes that simultaneously address industrial waste disposal challenges and soil stabilisation requirements at reduced cost. This study evaluates the geotechnical behaviour of black cotton soil (sourced from Nagpur district, Maharashtra) stabilised with fly ash (10%, 20% by dry weight), lime sludge from a calcium-carbide based acetylene plant (8%, 12% by dry weight), and a combined fly ash-lime sludge blend (8% lime sludge + 10% fly ash). Properties evaluated include Atterberg limits (liquid limit, plastic limit, plasticity index), free swell index, compaction characteristics (OMC, MDD), unconfined compressive strength (UCS) at 7, 14, and 28 days curing, California Bearing Ratio (CBR) under soaked conditions, and SEM/XRD microstructural analysis at 28 days to identify cementitious reaction products. The combined fly ash-lime sludge blend achieves a 28-day UCS of 562 kPa (205% above untreated soil) and a soaked CBR of 11.8% (321% above untreated soil), outperforming all individually stabilised mixes. The plasticity index reduces from 38.6% in untreated soil to 17.6% in the blended mix, and the free swell index reduces from 112% to 36% — a 68% reduction indicating substantial mitigation of swell-shrink potential. SEM and XRD analyses confirm the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) cementation products bridging soil particles, with the blended mix showing the most extensive cementitious matrix development at 28 days.

Keywords: *expansive soil, black cotton soil, fly ash, lime sludge, soil stabilisation, free swell index, unconfined compressive strength, California Bearing Ratio, SEM, XRD, pavement subgrade*

1. Introduction

Black cotton soils, classified predominantly as CH (highly plastic clay) under the Unified Soil Classification System, derive their high swell-shrink potential from a montmorillonite-dominated clay mineralogy with high cation exchange capacity and specific surface area, causing volumetric changes of up to 20-30% between dry and saturated states. These volumetric changes manifest in the field as differential heave and settlement of pavements, cracking of lightly loaded structures, and progressive deterioration of canal linings, with the Indian Roads Congress estimating annual maintenance costs running into hundreds of crores of rupees for highway sections constructed over expansive subgrades without adequate treatment.

Lime stabilisation operates through a combination of short-term modification — cation exchange and flocculation-agglomeration reactions that reduce plasticity and improve workability within hours to days — and long-term pozzolanic reaction, in which the high pH environment created by lime dissolution mobilises silica and alumina from the clay mineral structure to form cementitious calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels over weeks to months. Fly ash, while possessing limited self-cementing capacity in most Class F variants, provides additional pozzolanic silica and alumina that can react with the calcium hydroxide supplied by lime, extending and enhancing the cementitious reaction beyond what lime alone achieves at equivalent dosage.

Lime sludge, a calcium-rich by-product generated during the causticising process in paper manufacturing and during acetylene production from calcium carbide, typically contains 70-85% calcium carbonate and calcium hydroxide and represents a disposal burden for generating industries, often landfilled at significant cost. The hypothesis underlying this study's combined fly ash-lime sludge approach is that lime sludge can substitute for a portion of the calcium source conventionally provided by hydrated lime, while fly ash supplies the silica-alumina reactants, together producing a stabilisation system that addresses two industrial waste streams simultaneously while achieving stabilisation performance comparable to or exceeding conventional lime treatment at reduced material cost.

2. Materials, Mix Design and Test Methods

2.1 Materials Characterisation

The expansive soil was collected from a depth of 1.5-2.0 m at a site in Nagpur district, Maharashtra, and classified as CH per IS 1498:1970, with a liquid limit of 68.4%, plastic limit of 29.8%, plasticity index of 38.6%, and free swell index of 112% (per IS 2720 Part 40). X-ray diffraction confirmed montmorillonite as the dominant clay mineral, with minor illite and kaolinite. Class F fly ash (NTPC Koradha Thermal Power Station, fineness 310 m²/kg) had a SiO_2 + Al_2O_3 + Fe_2O_3 content of 88.4%. Lime sludge, obtained from a calcium-carbide based acetylene generation plant in Nagpur, was found by chemical analysis to contain 76.2% $Ca(OH)_2$ and $CaCO_3$, with the remainder comprising minor impurities and moisture, and was oven-dried and pulverised prior to use.

2.2 Mix Proportions and Specimen Preparation

Six mixes were proportioned: untreated soil (control), Soil+10%FA, Soil+20%FA, Soil+8%LS, Soil+12%LS, and Soil+8%LS+10%FA combined blend, all percentages by dry weight of soil. Standard Proctor compaction tests (per IS 2720 Part 7) were performed to determine optimum moisture content (OMC) and maximum dry density (MDD) for each mix. UCS specimens (38mm diameter, 76mm height) were compacted at OMC and MDD, sealed in polythene, and cured at 27±2°C for 7, 14, and 28 days prior to testing. CBR specimens were compacted in standard moulds, cured for 7 days, and soaked for 96 hours prior to testing per IS 2720 Part 16.

3. Experimental Results

3.1 Index Properties and Swell Behaviour

Figure 1 presents the index property and swell behaviour dataset. Panel A shows the reduction in Atterberg limits across all six mixes. The plasticity index reduces progressively with both fly ash and lime sludge content, with lime sludge producing a more pronounced reduction per unit dosage — 12% lime sludge reduces the plasticity index to 20.2% compared to 27.4% for 20% fly ash, reflecting lime sludge's higher available calcium content driving more extensive cation exchange and flocculation. The combined blend achieves the lowest plasticity index (17.6%), a 54.4% reduction from the untreated soil's 38.6%.

Panel B's free swell index comparison reveals that all stabilised mixes show substantial reduction relative to the untreated soil's 112%, with the combined blend achieving the lowest value (36%) — a 68% reduction that brings the soil from the IS classification of "high swelling potential" into the "low to moderate" category, a critical threshold for foundation design simplification. Panel C's compaction curves show that increasing lime sludge and fly ash content shifts the OMC upward and the MDD downward relative to the untreated soil, consistent with the flocculated, more open particle arrangement produced by cation exchange reactions, an effect well documented in lime-treated expansive clays.

3.2 Strength Development and Bearing Capacity

Figure 2 presents the strength and bearing capacity results. Panel A's UCS development curves show that all stabilised mixes gain strength progressively from 7 to 28 days, with the combined blend showing the steepest gain rate, reaching 562 kPa at 28 days compared to 184 kPa for the untreated soil — a 205% increase. The lime sludge mixes outperform the equivalent-dosage fly ash mixes at all curing ages, consistent with lime sludge's higher immediately available calcium driving faster early pozzolanic reaction, while the fly ash component in the combined blend contributes increasingly to strength gain between 14 and 28 days as its slower pozzolanic reaction with lime sludge-derived calcium hydroxide proceeds.

Panel B's soaked CBR comparison shows the combined blend achieving 11.8%, a 321% increase over the untreated soil's 2.8% — sufficient to qualify the stabilised subgrade for a substantially reduced pavement crust thickness per IRC:37 design guidelines, representing significant cost savings in pavement construction over expansive subgrades. The 12% lime sludge mix alone achieves 9.4%, indicating that lime sludge is the more effective individual stabiliser for bearing capacity improvement, with fly ash addition in the combined blend providing an incremental but meaningful further gain.

Table 1. Summary of Index Properties, Strength and Bearing Capacity by Mix Design

Mix ID	LL (%)	PI (%)	Free Swell Index (%)	UCS 28d (kPa)	CBR (%)
Natural Soil (Control)	68.4	38.6	112	184	2.8
Soil+10%FA	61.2	32.1	94	246	4.1
Soil+20%FA	55.8	27.4	78	312	5.6
Soil+8%LS	52.6	24.8	65	398	7.2
Soil+12%LS	47.3	20.2	48	486	9.4
Soil+8%LS+10%FA (Ternary)	44.1	17.6	36	562	11.8

LL = Liquid Limit; PI = Plasticity Index per IS 2720 Part 5; Free Swell Index per IS 2720 Part 40; UCS = Unconfined Compressive Strength per IS 2720 Part 10; CBR = California Bearing Ratio (soaked, 96-hour) per IS 2720 Part 16

3.3 SEM and XRD Microstructural Analysis

Figure 3 presents the microstructural analysis and cost comparison. Panel A's SEM micrographs at 28 days show the untreated soil retaining its characteristic platy, loosely arranged montmorillonite morphology, while the combined blend exhibits a dense matrix of needle-like and fibrous cementitious products bridging and coating clay particles, consistent with extensive C-S-H and C-A-H gel formation. The 12% lime sludge mix shows intermediate development, with cementitious products present but less continuously distributed than in the combined blend. Panel B's XRD patterns confirm the appearance of calcium silicate hydrate and calcium aluminate hydrate reflections in the lime sludge and combined blend specimens, absent in the untreated soil and present only as minor peaks in the fly ash-only mixes, supporting the SEM-based interpretation of cementitious matrix development as the primary strength-gain mechanism.

4. Discussion

The finding that lime sludge outperforms equivalent-dosage fly ash on both plasticity reduction and strength gain is consistent with lime sludge's substantially higher readily available calcium hydroxide content driving more immediate and extensive cation exchange and pozzolanic reaction, whereas fly ash's calcium content is largely confined to minor crystalline phases with limited early reactivity. The combined blend's superior performance across all measured properties supports the synergistic mechanism proposed in the introduction: lime sludge provides an early calcium hydroxide source that both flocculates the clay fraction and initiates pozzolanic reaction, while fly ash's silica-alumina content extends this reaction over a longer timeframe, producing more extensive cementitious matrix development by 28 days than either material achieves independently at comparable total dosage.

The combined blend's free swell index of 36% and CBR of 11.8% position it favourably for use as a stabilised subgrade or sub-base material in highway construction over expansive soil terrain, where the IRC:37 design framework permits substantial pavement crust thickness reduction for subgrades achieving CBR values above 10%. From a circular economy perspective, the combined approach addresses disposal challenges for two industrial by-product streams — fly ash, generated at scale by thermal power stations, and lime sludge, generated by paper and acetylene industries — while reducing reliance on quarried lime, a cost and carbon advantage that strengthens the economic case for adoption in regions where both by-products are locally available, as is the case across much of Maharashtra's industrial belt.

5. Conclusion

This study confirms that black cotton soil stabilised with a combined fly ash-lime sludge blend (8% lime sludge + 10% fly ash) achieves substantial improvements across all measured geotechnical properties, with plasticity index reduced by 54.4%, free swell index reduced by 68%, 28-day UCS increased by 205%, and soaked CBR increased by 321% relative to untreated soil. SEM and XRD analyses confirm that these improvements arise from extensive calcium silicate hydrate and calcium aluminate hydrate cementitious matrix formation, with lime sludge providing the primary early calcium source and fly ash extending pozzolanic reaction through 28 days. The combined blend's free swell index reduction to 36% moves the soil from the high to the low-moderate swelling category, a significant outcome for foundation and pavement design simplification. The combined fly ash-lime sludge stabilisation approach is recommended for highway subgrade and embankment applications over expansive soil terrain in regions where both industrial by-products are locally available.

References

[1] Al-Mukhtar, M., Khattab, S., & Alcover, J. F. (2012). Microstructure and geotechnical properties of lime-treated expansive clayey soil. Engineering Geology, 139, 17–27.
[2] Bell, F. G. (1996). Lime stabilization of clay minerals and soils. Engineering Geology, 42(4), 223–237.
[3] Cokca, E. (2001). Use of class C fly ashes for the stabilization of an expansive soil. Journal of Geotechnical and Geoenvironmental Engineering, 127(7), 568–573.
[4] Deshmukh, P., & Bhole, A. G. (2022). Stabilisation of black cotton soil using industrial by-products: fly ash and lime sludge. Indian Geotechnical Journal, 52(4), 712–725.
[5] IRC:37-2018. Guidelines for the Design of Flexible Pavements. Indian Roads Congress, New Delhi.
[6] IS 1498:1970. Classification and Identification of Soils for General Engineering Purposes. Bureau of Indian Standards, New Delhi.
[7] IS 2720 (Parts 5, 7, 10, 16, 40). Methods of Test for Soils. Bureau of Indian Standards, New Delhi.
[8] Little, D. N. (1995). Stabilization of pavement subgrades and base courses with lime. Kendall/Hunt Publishing.
[9] Phanikumar, B. R., & Sharma, R. S. (2004). Effect of fly ash on engineering properties of expansive soils. Journal of Geotechnical and Geoenvironmental Engineering, 130(7), 764–767.
[10] Sabat, A. K. (2012). Stabilization of expansive soil using waste ceramic dust. Electronic Journal of Geotechnical Engineering, 17, 3915–3926.
[11] Sharma, A. K., & Sivapullaiah, P. V. (2016). Strength development in fly ash and slag blended expansive soil. Soils and Foundations, 56(2), 205–212.
[12] Sivapullaiah, P. V., Sridharan, A., & Ramesh, H. N. (2000). Strength behaviour of lime-treated soils in the presence of sulphate. Canadian Geotechnical Journal, 37(2), 384–394.
[13] Thompson, M. R. (1966). Lime reactivity of Illinois soils. Journal of the Soil Mechanics and Foundations Division, 92(5), 67–92.