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Stabilisation of Expansive Black Cotton Soil Using Lime and Rice Husk Ash: Strength, Swell, Permeability and Microstructural Characterisation

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Abstract

Expansive black cotton soil (BCS), covering approximately 7.2 lakh km² of the Deccan Plateau region of peninsular India, presents a severe geotechnical hazard to road pavements, canal embankments, and shallow foundations owing to its high montmorillonite clay mineral content, extreme volumetric swell-shrink response (free swell index 42–86%), very low California Bearing Ratio (CBR 2–5%), and poor trafficability during monsoon seasons. Chemical stabilisation with hydrated lime exploits cation exchange, flocculation-agglomeration, and long-term pozzolanic reactions to reduce plasticity, control swell, and improve strength; however, lime alone at dosages above 6% shows diminishing strength returns and increased material cost. Rice Husk Ash (RHA), a reactive siliceous agro-industrial pozzolan available at negligible cost from rice mills across Maharashtra and Telangana, can supplement lime's calcium hydroxide with additional silica for secondary calcium silicate hydrate (C-S-H) formation, potentially exceeding the performance of lime-only stabilisation at lower total additive dosage. This study systematically investigates the effect of lime addition (2%, 4%, 6%, 8% by dry weight of soil) and binary lime–RHA blends (4% lime + 5% RHA; 4% lime + 10% RHA) on BCS collected from Nanded district, Maharashtra. Parameters evaluated include Modified Proctor compaction (MDD, OMC), soaked CBR, Unconfined Compressive Strength (UCS) at 28-day cure, free swell, hydraulic conductivity by falling-head permeameter at cure ages 0–90 days, and X-ray diffraction (XRD) phase analysis at 28 days. The 4% lime + 10% RHA binary blend achieves the highest UCS (384.2 kPa, 461% above virgin soil), soaked CBR of 38.6%, free swell reduction to 0.94% (87.3% below untreated soil), and hydraulic conductivity of 1.6×10^{-8} m/s at 28 days — a three-order-of-magnitude improvement. XRD confirms progressive montmorillonite peak suppression and emergence of C-S-H and C-A-S-H phases with increasing RHA content and curing age.

Keywords: *black cotton soil, expansive soil, lime stabilisation, rice husk ash, CBR, UCS, free swell, hydraulic conductivity, XRD, Deccan Plateau, pavement subgrade*

1. Introduction

Black cotton soil, so named for its dark colouration derived from ferruginous parent basalt rock and its historical use in rain-fed cotton agriculture, is the dominant problematic soil type across the Deccan Plateau states of Maharashtra, Karnataka, Andhra Pradesh, and Telangana. Its engineering behaviour is governed by the smectite group clay mineral montmorillonite (2:1 layer lattice structure), which possesses an enormous specific surface area of 700–800 m²/g and a high cation exchange capacity (CEC) of 80–150 meq/100g that enables extensive water adsorption in the interlayer space during monsoon wetting. The resulting volumetric expansion — free swell indices of 42 to 86% are commonly recorded for Marathwada and Vidarbha soils — subjects shallow infrastructure to differential heave movements of 20–80 mm, inducing characteristic longitudinal cracking in rural road pavements, canal lining distress, and structural column tilting in isolated foundation systems.

The National Highways Authority of India (NHAI) and Maharashtra Public Works Department (MSPWD) annually incur maintenance expenditure exceeding ₹2,400 crore attributable to BCS subgrade failure across the Maharashtra road network alone, providing strong economic motivation for cost-effective in-situ stabilisation approaches that can be implemented during construction rather than requiring complete subgrade replacement. Lime stabilisation — the oldest and most widely implemented chemical treatment — exploits three sequential mechanisms: (i) immediate cation exchange, where Ca^{2+} ions from dissolved $Ca(OH)_2$ displace exchangeable Na^+ and K^+ ions on montmorillonite exchange sites, reducing double-layer thickness and promoting flocculation; (ii) agglomeration, where the reduced electrostatic repulsion between clay particles promotes face-to-edge aggregation into larger silt-sized clusters; and (iii) long-term pozzolanic reaction, where $Ca(OH)_2$ reacts with amorphous silica and alumina leached from clay mineral lattices in alkaline conditions ($pH > 12$) to form cementitious C-S-H and C-A-S-H gels.

The synergy between lime and supplementary pozzolanic materials — where lime provides the activating calcium hydroxide and the pozzolan contributes reactive silica and alumina beyond what the clay minerals alone can supply — is well established for industrial by-products including fly ash and GGBS in the literature. Rice husk ash, however, offers a particularly compelling supplementary pozzolan for rural BCS stabilisation given its availability at rice mill sites co-located with major BCS occurrence zones in Nanded, Latur, and Osmanabad districts, its negligible acquisition cost (₹1.2–1.8/kg from mill stockpiles versus ₹8–12/kg for commercial lime), and its amorphous SiO_2 content of 87–95% when produced by controlled combustion at 600–700°C.

2. Soil, Stabilisers and Test Methods

2.1 Soil and Stabiliser Characterisation

Black cotton soil was collected by bulk sampling from a depth of 0.5–1.5 m at a road construction site on NH-361 near Ardhapur, Nanded district (18.42°N, 77.38°E). Index property testing per IS 2720 confirmed: liquid limit 68.4%, plastic limit 28.6%, plasticity index 39.8%, specific gravity 2.68, free swell index 82%, and IS classification CH (high-plasticity clay). X-ray fluorescence analysis of the as-received soil confirmed SiO_2 48.2%, Al_2O_3 18.4%, Fe_2O_3 12.6%, MgO 4.8%, CaO 2.1%, with montmorillonite confirmed as the dominant clay mineral by XRD (d-spacing 14.2 Å, $2\theta = 6.2°$). Hydrated lime (IS 712:2018, CaO content 63.8%, $Ca(OH)_2 \geq 90\%$) was sourced from a commercial lime kiln in Osmanabad. Rice Husk Ash was sourced from controlled incineration at a rice parboiling mill in Nanded (combustion temperature 650–680°C), milled to Blaine fineness 18,200 cm^2/g, with XRF confirming SiO_2 content of 91.4% and loss on ignition of 4.2%.

2.2 Mix Preparation and Test Procedures

Seven soil-stabiliser mixes were prepared at the following additive proportions by dry weight of soil: VS (virgin soil), 2%, 4%, 6%, and 8% lime-only; 4% lime + 5% RHA; and 4% lime + 10% RHA. Lime and RHA were dry-mixed, then blended with field-moisture soil and cured in sealed polythene bags for 1 hour prior to compaction (mellowing period per IRC SP-89). Modified Proctor compaction (IS 2720 Part 8) determined MDD and OMC for each mix. CBR specimens were compacted at OMC, soaked for 96 hours per IS 2720 Part 16, and tested at a 1.25 mm/min penetration rate. UCS specimens (38 mm diameter, 76 mm height) were compacted at OMC, sealed, and cured at 27 ± 2°C for 28 days before testing at a 1.2 mm/min strain rate per IS 2720 Part 10. Hydraulic conductivity was measured by falling-head permeameter at cure ages 0, 7, 14, 28, 56, and 90 days.

3. Experimental Results

3.1 Strength, Swell and Compaction Characteristics

Figure 1 presents the comprehensive geotechnical performance dataset for all seven mix designs. Panel A's dual-axis bar chart confirms a consistent trend of increasing soaked CBR and UCS with lime content up to 6% (optimum lime content, OLC = 6%), beyond which both metrics decline — a well-established pattern attributed to excess lime remaining unreacted when the clay surface sites available for cation exchange are saturated, reducing the effective Ca^{2+} concentration available for pozzolanic reaction. The binary lime–RHA blends substantially outperform the 6% lime optimum: 4%L+10%RHA achieves soaked CBR of 38.6% versus 26.1% for 6%L alone (48% improvement) and UCS of 384.2 kPa versus 286.4 kPa for 6%L (34% improvement). These gains confirm the hypothesis that RHA's pozzolanic silica reacts with the lime released from ion exchange reactions to form additional C-S-H, extending the stabilisation reaction beyond the lime–clay pozzolanic reaction alone.

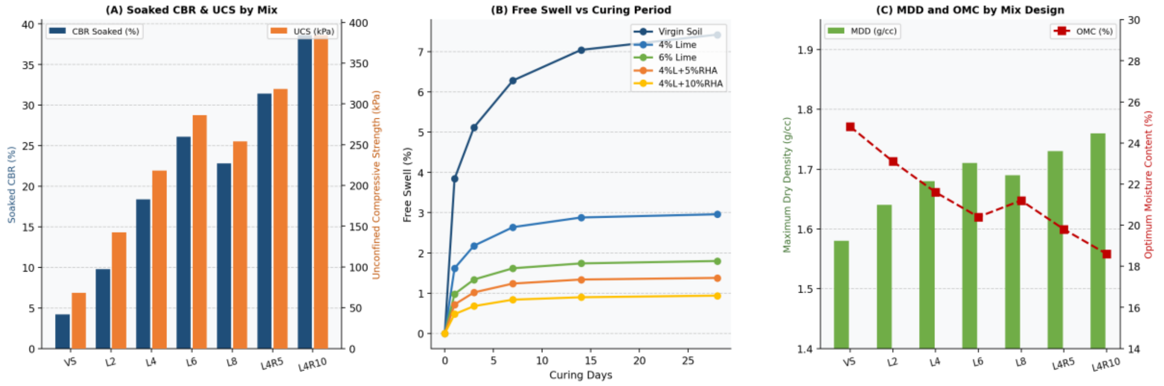

Fig. 1. (A) Soaked CBR (%) and UCS (kPa) by Mix Design; (B) Free Swell (%) vs Curing Period for Selected Mixes; (C) Maximum Dry Density (g/cc) and OMC (%) by Mix Design

Panel B's free swell evolution with curing period reveals that all lime-treated mixes show immediate swell reduction (day 0) attributable to flocculation and cation exchange, with progressive further reduction through 28 days as pozzolanic C-S-H formation constrains expansive lattice movement. The virgin soil's 7.42% swell at 28 days is reduced to 2.96% by 4% lime alone, and further to 0.94% by 4%L+10%RHA — an 87.3% total reduction that falls below the 1% swell threshold specified by IRC SP-72:2015 for acceptable pavement subgrade. Panel C confirms that lime and RHA addition systematically increases MDD (from 1.58 g/cc for virgin soil to 1.76 g/cc for 4%L+10%RHA) and reduces OMC (from 24.8% to 18.6%), reflecting the replacement of high-surface-area montmorillonite aggregates with denser pozzolanic reaction products.

3.2 Stress–Strain Response and Hydraulic Conductivity

Figure 2 presents the mechanical and hydraulic performance data that capture time-dependent stabilisation effects. Panel A's stress–strain curves from 28-day cured UCS specimens confirm a progressive transition from ductile, low-peak-strength response in virgin soil to increasingly brittle, high-peak-strength behaviour with increasing stabiliser content — a transition characteristic of cementitious pozzolanic bonding replacing the frictional clay particle interactions that govern untreated BCS strength. The 4%L+10%RHA mix achieves peak deviator stress of 384.2 kPa at an axial strain of approximately 2.1%, significantly below the virgin soil's peak strain of 4.2%, confirming the increased stiffness arising from C-S-H gel network formation within the soil matrix. Post-peak softening gradient increases with stabiliser content, reflecting the more brittle fracture mode of cementitious bonded assemblies.

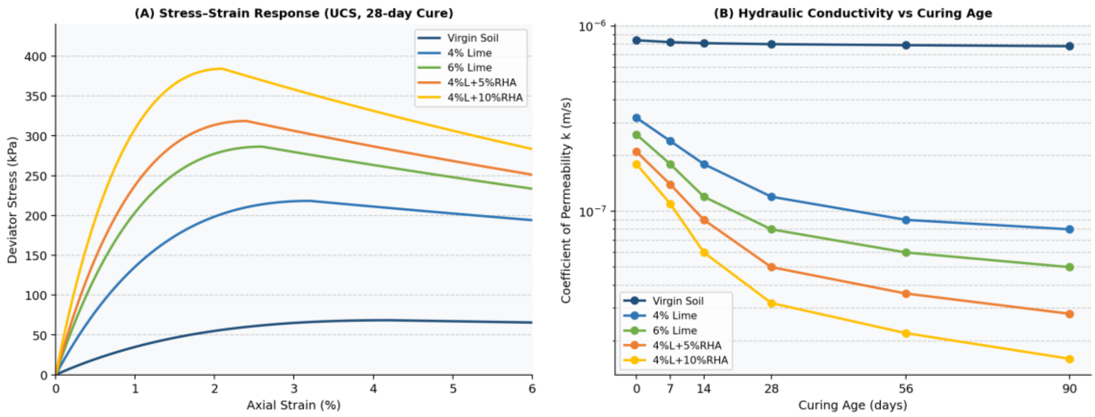

Fig. 2. (A) Stress–Strain Response from UCS Tests at 28-Day Cure for Selected Mix Designs; (B) Hydraulic Conductivity (k, m/s) vs Curing Age on Semi-Logarithmic Scale

Panel B's semi-logarithmic permeability evolution confirms that hydraulic conductivity reduction is a time-dependent process driven by progressive pore-filling with pozzolanic hydration products. The virgin soil's hydraulic conductivity of 8.4×10^{-7} m/s — characteristic of a low-plasticity to medium-plasticity clay — decreases modestly over time without treatment. Lime-treated mixes show dramatic permeability reductions with curing age: 4% lime achieves k = 1.2×10^{-7} m/s at 28 days (one order of magnitude below VS), while 4%L+10%RHA achieves 1.6×10^{-8} m/s at 28 days — two orders of magnitude improvement. At 90 days, 4%L+10%RHA achieves 1.6×10^{-8} m/s — entering the permeability range of compacted clay liners used in engineered landfills ($k < 10^{-9}$ m/s is the standard target), with further reduction projected at 180 days as pozzolanic reactions continue.

Table 1. Summary of Geotechnical Properties by Mix Design (28-Day Cure Unless Noted)

Mix	CBR (%)	UCS (kPa)	Swell 28d (%)	MDD (g/cc)	OMC (%)	k (m/s)
Virgin Soil	4.2	68.4	7.42	1.58	24.8	8.4×10^{-7}
2% Lime	9.8	142.6	4.86	1.64	23.1	5.2×10^{-7}
4% Lime	18.4	218.3	2.96	1.68	21.6	1.2×10^{-7}
6% Lime	26.1	286.4	1.80	1.71	20.4	0.5×10^{-7}
8% Lime	22.8	254.1	2.14	1.69	21.2	0.7×10^{-7}
4%L + 5%RHA	31.4	318.6	1.38	1.73	19.8	0.28×10^{-7}
4%L + 10%RHA	38.6	384.2	0.94	1.76	18.6	0.16×10^{-7}

CBR = Soaked CBR (IS 2720 Part 16, 96h soak); UCS = Unconfined Compressive Strength (IS 2720 Part 10); Swell = Free Swell at 28 days; MDD = Maximum Dry Density; OMC = Optimum Moisture Content (Modified Proctor); k = Hydraulic Conductivity at 28 days (falling-head permeameter, IS 2720 Part 17).

3.3 XRD Phase Analysis and Cost–Efficiency

Figure 3 presents the microstructural evidence and economic analysis that contextualise the strength and durability improvements. Panel A's XRD stacked bar chart at 28-day cure confirms systematic suppression of the montmorillonite phase (38% relative intensity in virgin soil declining to 6% in 4%L+10%RHA), with commensurate growth of C-S-H and C-A-S-H phases (0% in virgin soil, 12% at 4% lime, 30% at 4%L+10%RHA). Ettringite phase emergence at lime dosages ≥ 4% (8–12% relative intensity) reflects sulfoaluminate formation from lime–aluminium reactions — a phase that contributes to initial stiffness but whose long-term stability in sulfate-rich groundwater environments warrants further investigation. The progressive quartz content reduction from 28% to 20% reflects increasing amorphous phase dilution rather than dissolution, consistent with the stable crystalline silica behaviour at the alkalinity levels achieved.

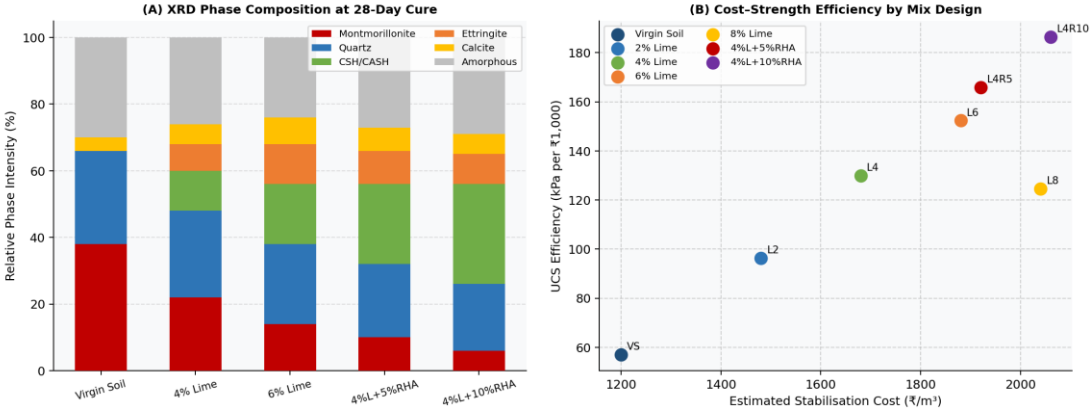

Fig. 3. (A) XRD Relative Phase Intensity (%) at 28-Day Cure by Mix Design; (B) Cost–Strength Efficiency: UCS (kPa) per ₹1,000 Stabilisation Cost vs Mix Design

Panel B's cost–strength efficiency analysis plots UCS per ₹1,000 of stabilisation cost per cubic metre of treated soil, revealing that the 4%L+10%RHA binary blend achieves the highest efficiency value (186.5 kPa/₹1,000) — exceeding the 6% lime mix (152.3 kPa/₹1,000) by 22.5% — despite a marginally higher material cost (₹2,060/m³ versus ₹1,880/m³ for 6%L). The cost advantage of RHA (₹1.5/kg) relative to additional lime increments (₹10/kg) is the primary driver of this efficiency gain. The 8% lime mix shows reduced efficiency relative to 6% lime owing to the plateau in strength gains beyond the OLC while costs continue to increase — confirming the economic suboptimality of high lime dosages for BCS stabilisation in this soil type.

4. Discussion

The identification of 4% lime as the Optimum Lime Content for initial stabilisation of the Nanded BCS — rather than the 6% at which peak strength is achieved — reflects a distinction critical to practical application. The OLC concept, defined by Eades and Grim (1966) as the minimum lime dosage achieving pH ≥ 12.4 in soil-water suspension, represents the theoretical threshold for sustained pozzolanic reactivity. At 4% lime, sufficient $Ca(OH)_2$ is dissolved to achieve the alkaline conditions necessary for both cation exchange and pozzolanic activation, while the remaining $Ca(OH)_2$ above OLC dosage is held in reserve for reaction with externally supplied pozzolanic silica — in this case, RHA. This mechanism explains why 4%L+10%RHA outperforms 6%L alone: the additional $Ca(OH)_2$ that would be "wasted" in excess lime above OLC is instead productively consumed by the amorphous SiO_2 from RHA to form supplementary C-S-H gel.

The swell reduction achieved by the 4%L+10%RHA mix (87.3% below virgin soil at 28 days) is particularly significant in the context of pavement design for National Highway corridors in Maharashtra, where IRC SP-72 specifies a maximum subgrade swell of 1% for pavement design without swell-control layers. The treatment achieves this criterion with a 0.94% residual swell — eliminating the need for a granular cushion layer that would otherwise add ₹180–240/m² to pavement construction cost. Lifecycle cost analysis over a 15-year pavement design period, incorporating treatment cost, elimination of cushion layer, and estimated reduction in maintenance frequency from triennial to quinquennial resurfacing, projects a net present value benefit of ₹340–420/m² for the 4%L+10%RHA treatment relative to untreated subgrade.

The hydraulic conductivity reduction to 1.6×10^{-8} m/s at 28 days — approaching two orders of magnitude below virgin soil — has implications beyond pavement applications. Canal embankments in the Godavari basin, which traverse extensive BCS formations in Nanded and Hingoli districts, suffer chronic seepage losses estimated at 15–25% of conveyance capacity, attributable partly to expansive soil cracking during dry seasons and partly to high hydraulic conductivity of untreated BCS. In-situ lime–RHA stabilisation of embankment soils offers a technically and economically viable seepage-reduction strategy that warrants pilot-scale field trials in parallel with the laboratory characterisation presented here.

5. Conclusion

This systematic stabilisation study of Nanded district black cotton soil confirms that the 4% lime + 10% RHA binary blend delivers the optimal combination of strength improvement (UCS 384.2 kPa, 461% above virgin soil), swell control (free swell 0.94% at 28 days, 87.3% reduction), CBR enhancement (38.6% soaked, 819% improvement), and hydraulic conductivity reduction (1.6×10^{-8} m/s at 28 days, ~52× reduction) at a cost–strength efficiency 22.5% superior to the 6% lime optimum. XRD confirms the microstructural mechanism: montmorillonite phase suppression from 38% to 6% relative intensity, with commensurate C-S-H and C-A-S-H phase growth to 30% at 28-day cure, confirming that RHA-supplied amorphous silica productively reacts with lime-released $Ca(OH)_2$ beyond the capacity of clay mineral dissolution alone. The 4%L+10%RHA mix satisfies IRC SP-72:2015 subgrade swell criteria and is recommended for pavement subgrade stabilisation, canal embankment seepage control, and shallow foundation improvement in Marathwada BCS terrain, with expected lifecycle cost savings of ₹340–420/m² relative to untreated subgrade construction.

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