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Review on Stabilization Techniques for Black Cotton Soil Using Various Materials

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Abstract

Black cotton soil (BCS), also known as expansive soil, poses significant challenges in civil engineering due to its high swell-shrink potential, low bearing capacity, and poor shear strength. This review synthesizes findings from 18 recent and historical studies on BCS stabilization, focusing on chemical, mechanical, waste-based, bio-enzyme, and advanced predictivemethods.Materialssuchaslime,cement,flyash,industrialwastes(e.g.,copperslag, FGD gypsum, construction demolition waste), geosynthetics (e.g., geonet, fibers), and bio-enzymes(e.g.,Terazyme)havebeenevaluatedforimprovingpropertieslikeCaliforniaBearing Ratio (CBR), Unconfined Compressive Strength (UCS), Atterberg limits, and compaction characteristics. Key outcomes highlight sustainable waste utilization for enhanced soil performance, with optimal mixes achieving up to 12-fold CBR improvements. The review underscores the need for eco-friendly, cost-effective approaches in road subgrade and foundation applications, while identifying gaps in long-term durability and field-scale validation.

Key-Words:- Black Cotton Soil, Soil Stabilization, California Bearing Ratio, Unconfined Compressive Strength, Sustainable Materials

1. Introduction

Black cotton soil (BCS) is a montmorillonite-rich clay prevalent in regions like India,Africa, andpartsofAsia,characterized byhigh plasticity,lowshearstrength,and volumetricinstability due to moisture fluctuations. These properties lead to differential settlement, cracking in structures, and reduced load-bearing capacity, making BCS unsuitable for direct use in construction, particularly as subgrade material for roads and pavements. Stabilization techniques aim to modify BCS's physical and mechanical properties by altering its microstructure, reducing swell potential, and enhancing strength.

Over the years, researchers have explored diverse stabilizers, including chemical additives (e.g., lime, cement), mechanical reinforcements (e.g., fibers, geonets), industrial by-products (e.g.,flyash,slag),andbio-enzymes.Thisreviewcompilesinsightsfromexperimentalstudies, focusing on laboratory tests such as Atterberg limits, compaction, CBR, UCS, and microstructural analyses. The literature spans from 1996 to 2025, emphasizing sustainable practices like waste recycling to address environmental concerns and cost inefficiencies. Categorization by stabilization method reveals trends in efficacy, optimal dosages, and potential synergies.

2. **Chemical Stabilization**

Chemical stabilization involves additives that induce pozzolanic reactions, flocculation, or cationexchangetoimproveBCSproperties.Limeandcementaretraditionalstabilizers,often combined with other materials for enhanced performance.

SIVAPULLAIAHietal.(1996)investigatedflyash'simpactonBCSindexproperties,noting significant reductions in liquid limit (LL), plastic limit (PL), and free swell due to pozzolanic reactivity and grain size effects.Addition of lime further amplified these benefits, improving workability without increasing swell potential. Similarly, Mehta et al. (2014) analyzed lime stabilization, reporting decreased plasticity index (PI) and increased CBR, attributing improvements to flocculation and cementitious bonding.

Clementine et al. (2024) stabilized BCS with silica sand (up to 8%) and lime (2%), achieving UCS of 188.39 kPa and soaked CBR of 12.3%, meeting subgrade standards. The silica sand reduced compressibility, while lime enhanced chemical bonding. Ramesh et al. (2025) used sandandcement,observingoptimalimprovementsinAtterberglimits,compaction,UCS,and CBR, highlighting cement's role in subgrade pavement applications.

AdvancedoptimizationsincludeLinganagoudaretal.(2025),whoemployedresponsesurface methodology (RSM) for BCS stabilized with FGD gypsum (3.41%) and cement (9.24%), yielding high UCS and CBR with reduced PI. N et al. (2024) focused on FGD gypsum alone, finding optimal dosages that decreased plasticity and increased UCS, promoting its use as an eco-friendly by-product from power plants.

Ikeagwuanietal.(2019)combinedsawdustash(16%)withlime(4%),resultinginpozzolanic reactions evidenced by X-ray diffraction (XRD) and scanning electron microscopy (SEM), leading to optimal CBR and specific gravity increases.

3. MechanicalStabilization

Mechanical methods reinforce BCS through physical interlocking, drainage improvement, or stress distribution using geosynthetics or fibers.

Poudel et al. (2025) enhanced BCS stability with geonet grains, evaluating water content, specific gravity, grain size, LL, proctor compaction, direct shear, and permeability. Geonet improved shear strength and reduced permeability, making it suitable for cost-effective stabilization.

Umesh Patel (2025) stabilized BCS using GGBS with polypropylene fibers, focusing on strength fulfillment for bachelor-level projects, though details on optimal mixes werelimited.

Sankhat (2024) improved CBR using geotextiles, plastic rings, shavings, and fibers, creating voids for better drainage and reducing settlement. Geotextiles minimized lateral movement, while fibers enhanced stress distribution.

4. StabilizationUsingWasteMaterials

Waste utilization addresses environmental concerns while providing economical stabilizers. Industrial and construction wastes have shown promise in BCS treatment.

Sahu et al. (2019) used copper slag (CS) at 20% optimal mix, reducing swell from 100% to 20.4%,increasingCBRto12.5%,andimprovingcompactionandtriaxialstrengthforlow-cost infrastructure.

Onyelowe et al. (2025) applied machine learning (ANN, GP, EPR) to predict BCS improvements via partial displacement with quarry dust and fly ash, achieving high CBR (R^2=0.983) and UCS (R^2=0.960), outperforming traditional models for sustainable road construction.

Deeraj et al. (2025) stabilized BCS with recycled glass and plastic granules, reducing construction costs by 50% while improving compaction and CBR through voids and reinforcement.

Gaikwad et al. (2024) treated BCS with construction demolition waste (5-25%), enhancing UCS after 28-day curing via microstructural changes in gradation, cohesiveness, and mineralogy.

Tsegaye Woldesenbet (2023) used plastic bottles and crushed glass wastes (up to 24% glass, 8% plastic), boosting UCS from 91.92 kPa to 688.83 kPa and CBR from 2.64% to 17.5%, leveraging geomechanical reinforcement.

5. Bio-EnzymeandPolymerStabilization

Bio-enzymes and polymers offer non-toxic, biodegradable alternatives for eco-friendly stabilization.

Chakrapani(2025)studiedTerazymeonBCS,butdetailedoutcomeswerenotfullyelaborated.

Gaikwad et al. (2024) used enzymes and acrylic polymers, optimizing dosages for reduced Atterberglimits,improvedcompaction,andshearstrength,emphasizingcost-effectivenessand sustainability.

6. Discussion

Across studies, stabilizers consistently reduce PI, LL, and swell while increasing CBR and UCS. Optimal dosages vary: 20% CS (Sahu et al., 2019), 16% sawdust ash + 4% lime (Ikeagwuani et al., 2019), and 8% silica sand + 2% lime (Clementine et al., 2024). Waste materials like fly ash, FGD gypsum, and plastics promote sustainability by repurposing by-products, aligning with circular economy principles. Microstructural analyses (SEM, XRD) confirm flocculation, agglomeration, and pozzolanic reactions as key mechanisms.

Challenges include variability in waste composition, long-term durability under field conditions, and scalability. Advanced tools like RSM (Linganagoudar et al., 2025) and ML (Onyelowe et al., 2025) enable precise optimization, reducing trial-and-error. Hybrid approaches (e.g., chemical + waste) yield superior results, but bio-enzymes require further validation for widespread adoption.

Gaps persist in comparative life-cycle assessments, environmental impact studies, and real-world applications beyond lab tests.

7. Conclusion

1. Stabilization of Stabilization of black cotton soil (BCS) is critical for ensuring safe and economical infrastructure, addressing challenges like high swell-shrink potential and low bearing capacity.
2. Chemical stabilizers (e.g., lime, cement), mechanical reinforcements (e.g., geonets, fibers), and waste materials (e.g., copper slag, fly ash, FGD gypsum) effectively enhance BCS engineering properties, including CBR, UCS, andAtterberg limits.
3. Waste-based stabilization, using industrial by-products and recycled materials, promotes sustainability by reducing environmental impact and construction costs, aligning with circular economy principles.
4. Hybrid approaches combining chemical and waste materials (e.g., FGD gypsum + cement, sawdust ash + lime) yield superior strength and stability outcomes compared to single-material methods.
5. Bio-enzymes and polymers offer eco-friendly, biodegradable alternatives for BCS stabilization, showing promise for cost-effective and sustainable applications.
6. Advancedtechniqueslikeresponsesurfacemethodology(RSM)andmachinelearning (e.g., ANN) enable precise optimization of stabilizer dosages, improving design efficiency.
7. Future research should prioritize field-scale trials, long-term durability assessments, and comprehensive life-cycle analyses to validate laboratory findings and ensure practical implementation.

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