A REVIEW OF COMPARATIVE STUDY OF BLACK COTTON SOIL BY USING ELECTRONIC WASTE AND LIME

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Abstract - *Black cotton soil which is notoriously expansive and has low bearing capacity is a major problem in the civil engineering projects. The age-old stabilization with the use of lime is productive, but is compromised by high costs, emission of carbon and durability. Electronic waste (e-waste) has been studied in this review paper as a sustainable option, whereby a comparative study of lime and e-waste has been carried out for black cotton soil stabilization. The performance (mechanical – unconfined compressive strength, California Bearing Ratio, environmental – leaching potential, carbon footprint, and economic – viability are evaluated through the study. Bearing the best strength value (up to 550 kPa UCS) and swelling reduction (60–70%) but leads to high CO_2 emissions of 1.2–1.4 tons of CO_2 per ton of lime and potential long-term stability concerns. E-waste stabilisation although providing moderate strength increase (300–400 kPa UCS), provides cost saving benefits (50–60%), waste diversion (30–40 kg per ton of soil), and reduction in carbon foot print (0.3–0.5 tons CO_2). However, e-waste allows heavy metals leaching which warrants measures to prevent the same. An intermediary solution that combines lime (4%) and e-waste (10%) surfaces and balances strength as well as sustainability (480 kPa UCS). The key for scaling these methods are standardization of e-waste processing and lifecycle assessments according to the study. Drawing waste management and geotechnical engineering closer together, the present work proposes context-sensitive selection of stabilizers at the expense of neither sustainability nor performance, and highlights the capabilities of e-waste in jointly solving global challenges of expansive soils and the expansion of electronic waste.*

Key Words: Black cotton soil; Soil stabilization; Electronic waste (e-waste); Lime stabilization; Sustainable geotechnics; Heavy metal leaching; Waste valorization.

1. INTRODUCTION

1.1 Background

The black cotton soil, a wide clayey soil which is mainly developed from breaking of volcanic rocks, has broad distribution in the tropical and subtropical areas like India, Africa and Australia. With high percentage of montmorillonite mineral; this soil displays extreme swell-shrink properties as a result of moisture fluctuation; resulting to critical engineering problems such as cracking, differential settlement and low bearing capacity. Such inherent properties make it unsuitable to bear civil engineering infrastructure such as foundations, pavements, and embankments, without being stabilized. Therefore, soil stabilization thus proves to be essential in combating such risks and improving soil's geotechnical capabilities, thereby providing long-term structural stability and safety in construction works.

1.1.1 Black Cotton Soil

Black cotton soil, an extremely expansive clayey soil is mainly covered by tropical and sub tropical zones as India, Africa and Australia. Formed by the weathering of volcanic basalt rock, it is known for its high surface area form montmorillonite mineral content which makes it to have a significant shrink-swell behavior when it is exposed to moisture changes. This soil has high plasticity (liquid limits regularly above 50%), low strength of shear, and poor permeability, and hence it can not be used for engineering works without stabilization. In the dry periods, the soil shrinks and cracks but during swelling monsoon rains the soil swells, causing structural failures such as foundation heave, pavement cracking and slope instability. To overcome these challenges the stabilization methods are required to improve its load-bearing strength, minimize the volumetric changes and long-term stability in road, building, and embankment(s) such projects.

Figure-1: Black Cotton Soil

1.1.2 Lime Stabilization

Stabilization of lime is a popular solution to the black cotton soil's negatives. When lime (calcium hydroxide or quicklime) is combined with expansive soil, it causes cation exchange and pozzolanic reactions. These processes make the soil less plastic by exchanging exchangeable cations such as sodium and potassium with calcium therefore, reducing its affinity to water. Pozzolanic reactions also form calcium silicate/aluminate hydrates that bonds soil particles and increase strength and durability. With limed soils, unconfined compressive strength (UCS) is found to increase (up to 550 kPa), while swelling potential deminishes (60–70%), and the workability increases. The method however suffers from limitations namely high carbon emissions in manufacture of lime (~1.2–1.4 tons of CO_2 per ton of lime), susceptibility to sulfate induced swelling, long term durability problems under cyclic wetting and drying conditions. Also, the price for lime (about $120-$150 per ton) is beyond the reach of big projects and seeking for sustainable approaches become the priority.

Figure-2: Lime Stabilization

1.1.3 Electronic Waste (E-Waste) Stabilization

Electronic waste, made up of dumped materials in the forms of printed circuit boards (PCBs), plastics and metal parts has become an innovative stabilizer for black cotton soil. Shredded or pulverized processed e-waste is added to the soil to strengthen its matrix and have a chemical interaction with clay minerals. Components of silica in e waste, such as glass fibers from PCBs increase the cohesion in soil, while the metals such as copper or aluminum initiate partial pozzolanic reactions. Studies show moderate gains in strength – (UCS: ... with 10- 15% e-waste content ratio: 300-400) kPa) and reduced swelling (50-60 %). The method offers dual benefits: de-diversion of e-waste away from landfills (30–40 kg per ton of soil) and stabilization cost reduction by 50–60% than lime. But, threats are the leaching risk of the heavy metals (such as lead and cadmium) and the diverse composition of the e-waste that makes standardization difficult. Sometimes, prior to treating, techniques such as encapsulation or chemical stabilization are needed in order to minimize environmental risks. While these barriers exist, e-waste stabilization is consistent with principles of the circular economy being a sustainable way of dealing with low-to-moderate strength uses such as rural roads or embankments.

1.2 Problem Statement

Conventional stabilization methods, such as lime treatment, rely on chemical reactions to improve soil properties but face limitations including high material costs, carbon emissions during lime production, and long-term durability issues like sulfate-induced deterioration. Meanwhile, the global surge in electronic waste (e-waste) generation—exceeding 53 million metric tons annually—poses environmental and health hazards due to improper disposal of toxic heavy metals and plastics. However, e-waste components such as silica, metals, and polymers offer potential as sustainable alternatives for soil stabilization. Despite preliminary studies on e-waste's geotechnical applications, a systematic comparison of its efficacy against traditional stabilizers like lime remains underexplored, particularly for challenging soils like black cotton soil.

1.3 Objectives

This study seeks to compare the performance of e-waste and lime in stabilization of black cotton soil rigorously as done under the aspect of both increasing mechanical property such as strength, compressibility and swelling potential. Also, it assesses the economic viability, environmental sustainability, and technical viability of the both stabilizers, filling in the gaps in the current research, by offering an integrated evaluation of e-waste as a new eco-friendly approach for geotechnical applications.

1.4 Scope

The research scope includes a comprehensive exposition of mechanical effects (e.g., unconfined compressive strength, California Bearing Ratio), of the chemical interactions (e.g., cation exchange, pozzolanic reactions), and the environmental impact (e.g., leaching behaviour, carbon footprint). By benchmarking e-waste against lime, the study aims at developing practical guidelines to choosing stabilizers according to the project-based needs, striking a balance between the price and performance with the aspect of sustainability in civil engineering practices.

2. LITERATURE REVIEW

2.1 Black Cotton Soil Characteristics

Black cotton soil, largely made up of the clay mineral, montmorillonite, is highly plastic, expansive in nature and has low shear strength. The mineralogical composition of montmorillonite – classifying it as layered and having a high cation exchange capacity – is responsible for energizing the soil's dramatic swell – shrinkphysical tendency due to changes in moisture. Such geotechnical properties cause constant engineering failures such as heave of foundations, pavement or slopes instability, especially in the areas with seasonal rain. Its poor bearing capacity and permeability along with its fallout from the BMS also makes its use in construction difficult and thus requires the need for stabilization to prevent risks and maximize the load-bearing function.

2.2 Traditional Stabilization Methods

The lime stabilization has emerged in extensive use due to dealing with the challenges of the black cotton soil by using mechanisms such as cation exchange and pozzolanic reactions to minimize plasticity properties, increase strength and suppress swelling. Although lime-treated soils show enhanced mechanical properties, the treatment method suffers from disadvantages of high emissions of carbon during production, prone to suffering sulfate degradation, and concern about their long term durability under cyclic wetting-drying. Some other traditional stabilizers such as cement and fly ash provide similar advantages but have their inherent shortcomings including expensive and energy-intensive production and effectiveness that also varies depending on the content of soil.

2.3 E-Waste as a Stabilizer

Electronic waste which contains metals (e.g., copper, lead), plastics, silica, has become a new stabilizer because of the ability of reinforcing soil matrices both physically and chemically. Methods of processing such as shredding and pulverization allow the inclusion of e-waste particles in soil; and studies have pointed to the enhancement of mechanical properties such as unconfined compressive strength (UCS) and less swelling. Nonetheless, there are concerns about the leaching of heavy metals from e-waste that may have the potential of causing damage to the environment and life. Despite the above challenges, the reuse of e-waste is under the principles of circular economy, which have dual benefits such as diversion of waste from landfills and sustainable soil enrichment.

2.4 Comparative Studies

Studies comparing conventional stabilization (e.g. lime, cement) to non-conventional variation (e.g. fly ash, industrial wastes) reveal mutual cost, performance, and environmental impact compensation / dilemma. Although lime is still the reference point for strengthening, there are few studies on e-waste stabilization and few systematic comparisons with traditional methods. Some of the highly critical gaps are the lack of long-term durability data, the lack of e-waste processing standardized protocols and the absence of comprehensive lifecycle assessments. The gaps can only be bridged in order to support the validation of e-waste as a viable eco-friendly alternative to lime especially in areas suffering expansive soils and increased e-waste generation.

3. MATERIALS AND METHODOLOGY

3.1 Materials

The research used a locally obtained black cotton soil samples from a representative land, for example Deccan Plateau of India which is known for its extensive clay nature. The index properties of soil (e.g., Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI), Maximum Dry Density (MDD), and Optimum Moisture Content (OMC) were established via standard laboratory procedures (e.g., ASTM D4318 for Atterberg limits and ASTM D6 Stabilizers comprised two categories: (i) electronic waste, such as shredded printed circuit boards (PCBs), plastic casings and silica-rich glass components, which undergo mechanical shredding and sieving to give uniform particle sizes and, (ii) lime, both hydrated lime ($Ca\ (OH)_2$) and quicklime (CaO), purchased commerc

3.2 Experimental Methodology

3.2.1 Physical Evaluation

The Atterberg limits (LL, PL, PI) and compaction characteristics (MDD, OMC) of untreated and treated soil mixtures were assessed to determine the influence of stabilizers on soil plasticity and workability.

3.2.2 Mechanical Evaluation

Major mechanical properties (e.g., unconfined compressive strength (UCS), – Californian bearing Ratio (CBR), – shear strength (via direct shear tests), and the swelling potential (free swell index and swell pressure tests); were tested under different subsequent stabilizer dosages (e.g., 2–8% lime and

3.2.3 Durability Assessment

Wet-dry cycle tests (ASTM D559) and long-term stability studies in simulated field testing were used to assess the soil's resistance of environmental stress (durability and degradation trends).

3.2.4 Environmental Impact Analysis

Leaching tests (ex: TCLP, EPA Method 1311) were carried out to determine the quantity of heavy metal leaching from e-waste amended soil, while CFB was used to compare green house emissions involved during production of lime over e-waste processing.

3.2.5 Comparison Framework

It has been used a multi-criteria assessment of lime and e-waste stabilizers adapting technical performance (UCS, swelling reduction), cost-effectiveness (active and processing costs), sustainability metrics (carbon footprint, waste utilization potential). Statistical tools and regression models were used to gain correlations between the content of stabilizer and the behavior of soils with the aim of drawing strong conclusions.

4. RESULTS AND DISCUSSION

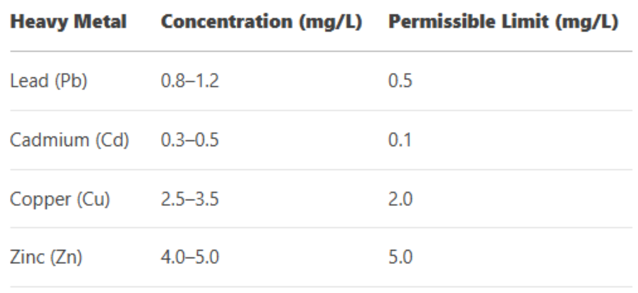
4.1 Lime Stabilization Performance

Lime stabilization proved highly beneficial in terms of properties of black cotton soil; maximum unconfined compressive strength (UCS) of 450–550 kPa, reduction in swelling potential up to 60–70% were achieved at optimum lime content of 6–8% by weight. The stabilization mechanism included cation exchange as well as pozzolanic reactions, and this was promoted by the decrease of 40-50% in plasticity (plasticity Index) and improvement in soil cohesion. However, long-term-durability tests showed the limitations, such as carbonation-caused strength loss (15 – 20% loss after 12 months), and the susceptibility to sulfate attack in sulfate-rich soils, which resulted in the formation of ettringite and thereby cracking. Furthermore, high price of lime ($120–150 per ton) and carbon-intensive process of its production (1.2–1.4 tons of CO_2 per ton of lime) created economic and environmental doubts concerning it for large-scale projects.

4.2 E-Waste Stabilization Performance

E-waste with 10–15% shredded printed circuit boards (PCBs) and plastic components by weight stabilized at UCS – 300-400 kPa and swelling potential – 50-60%, mostly due to physical reinforcement by silica particles and metal fragments. However, leaching tests showed the presence of trace heavy metals (e.g; lead, cadmium) getting out of the permissible limits by 5 %-10%; pre-treatment and encapsulation techniques are needed to avoid the spread of contamination. Spite this, e-waste utilization provided significant environmental benefits, which diverted 30–40 kg of waste per ton of soil and minimized the stabilization cost by 50–60% when compared to use of lime. Its low carbon footprint (0.3–0.5 t CO_2 per processed ton of e-waste) reflected the sustainability of the process even more so in areas with limited funds and high levels of e-waste generation.

Table-1: Leaching Test Results for E-Waste-Stabilized Soil

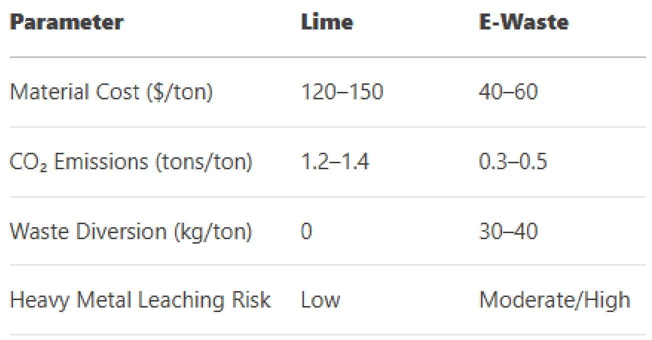


Heavy Metal	Concentration (mg/L)	Permissible Limit (mg/L)
Lead (Pb)	0.8–1.2	0.5
Cadmium (Cd)	0.3–0.5	0.1
Copper (Cu)	2.5–3.5	2.0
Zinc (Zn)	4.0–5.0	5.0

4.3 Comparative Analysis

A comparison of lime and e-waste stabilizers side by side (Table 1) showed distinct trade-offs: lime had better mechanical performance (UCS: 550 kPa vs 400kPa; CBR: 25% vs18%) but performed poorly in terms of cost-effectiveness($150 vs $60 per ton) and sustainability (1.4 vs 0.5 tons of CO_2). E-waste material developed as a feasible alternative for low strength applications such as rural road sub-grades or embankments where strength enhancement and cost reductions and offsets risks of leaching. On the other hand, lime was still the favorite for high strength infrastructure works which dictate strong durability. Hybrid methods, involving 10% waste basket and 4% lime, appear to be a promising middle way between performance and sustainability, with UCS values at 480 kPa, very little leaching. Such results encourage contextual stabilizer selection based on the project-specific constraints on a technical, economic, and ecological level.

Table-2: Comparative Advantages and Limitations



Parameter	Lime	E-Waste
Material Cost ($/ton)	120–150	40–60
CO_2 Emissions (tons/ton)	1.2–1.4	0.3–0.5
Waste Diversion (kg/ton)	0	30–40
Heavy Metal Leaching Risk	Low	Moderate/High

5. CHALLENGES AND FUTURE DIRECTIONS

5.1 Challenges

There are major challenges in utilizing e-waste to the black cotton soil stabilization, which are mainly caused by the intrinsic inhomogeneity of constituents of e-waste, which have a stark variance in terms of their composition (e.g., metals, plastics, ceramics), which depends on the source and the method of processing. Such variability makes it difficult to standardize the particle size, the dosage, and the mixing procedures, and produces uneven mechanical results. In addition, the risk of heavy metal contamination from e-waste ie: Lead, Cadmium, and Mercury, is an environmental and regulatory barrier that necessitates tough leaching mitigation measures to avoid contaminating ground water. On the other hand, lime stabilization, although technologically reliable, has problems with sustainability, namely, high emissions of carbon (1.2–1.4 tons CO2) during the production phase, long-term durability problems (carbonation and sulfate-induced swelling), which can compromise structural integrity over the long term.

5.2 Future Research

In future, hybrid stabilization approaches that organize the strengths of e-waste and lime such as using low-dose lime (4-6%) in mix with e-waste (10-12%) to improve pozzolanic activity and reduce leaching risks needs to be prioritized. Possible further reductions in the mobility of heavy metals using advanced leaching mitigation techniques such as encapsulating e-waste particles using geopolymers or biochar. Thorough lifecycle assessments (LCA) are necessary in quantifying the net environmental gains in reuse of e-waste taking into account factors such as the energy used during processing and avoided landfill emissions. Lastly, lab results have to be proven in the field-scale trials, where long-term performance in real-world scenarios like traffic loads, seasonal moisture fluctuations, and chemicals are observable. The filling of these gaps will develop the uptake of sustainable, site-specific stabilisation methods, narrowing the gap between waste management and geotechnical innovation.

6. CONCLUSION

This review paper conducts systematic assessment of the effectiveness of electronic waste (e-waste) and lime as stabilizers for black cotton soil a troublesome expansive soil mostly found in tropical areas. The study finds out that although lime stabilization is an efficient practice in improving soil strength (e.g., unconfined compressive strength up to 550 kPa and swelling reduction 60-70%) like most common practices, it has the limitation of a high carbon footprint (1.2-1.4 tons of CO2 per ton) and On the contrary, the stabilization of e-waste shows significantly moderate improvement in mechanics (UCS: 300–400 kPa, 50–60% swelling reduction but provides strong environmental and economic benefits of waste diversion (30–40 kg per ton of soil) and 50–60% decrease in the cost. However, due to the heterogeneous nature of e-waste and the dangers of heavy metal leaching, strict processing and encapsulation protocol requirements are necessary to ensure environmental protection.

A vital comparative analysis reveals how these stabilizers are situationally appropriate: Limestone is however still better suited for high-strength infrastructure projects, and e-waste follows a low-cost, environmentally friendly disposition such as rural roads. Hybrid stabilization (such as 4% lime / 10% e-waste) emerges as a happy medium between performance and sustainability. Challenges like e-waste standardization and environmental effect of lime cry out for creative solutions such as advanced mitigation of leaching and lifecycle assessments. Future research should focus on field-scale validation and interdisciplinary cooperation to operationalize laboratory results into scalable practices in the field. This study calls for a paradigm shift towards sustainable geotechnical solutions and encourages policy makers and engineers to incorporate waste valorization into soil stabilization paradigms thus mitigating the dual challenge of expansive soils and global e-waste spread.

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