

Correlating Micro-Mineralogy with Seismic Optimization & Structural Response of Transmission Infrastructure on Geopolymer-Stabilized Subgrades

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Abstract—The increasing demand for electrical energy necessitates the development of economical and lightweight transmission line towers. However, constructing these lifeline structures on Black Cotton Soil (BCS) poses significant civil engineering challenges due to the soil's expansive nature and high montmorillonite content, which leads to unequal foundation settlement and low bearing capacity. This research presents a dual-phase approach: first, stabilizing the problematic BCS using Construction and Demolition (C&D) waste-based geopolymers, and second, evaluating the structural response of a 40 m transmission tower with varying bracing patterns (single, double, and knee) resting on this stabilized stratum. Utilizing STAAD.Pro software for dynamic structural analysis and advanced micro-mineralogical testing (XRD analysis) for soil evaluation, the study aims to achieve the most stable, economical tower configuration and a resilient foundation.

Keywords: Response Spectrum, Geopolymer, Soil Stabilization, and Transmission Tower etc.

I. INTRODUCTION

Here is an expanded and highly detailed Introduction for your paper. It incorporates the rich, literature-backed context you provided regarding the mechanics of Black Cotton Soil (BCS) and the sustainability of Construction and Demolition Waste (CDW), while seamlessly tying it into the structural and seismic analysis of the transmission towers from your previous data.¹ Introduction High-voltage transmission towers are critical lifeline structures that must frequently be constructed across diverse and challenging terrains to meet the nation's growing electrical demands. A significant hurdle in the foundational design of these structures is the presence of Black Cotton Soil (BCS). Renowned for its highly expansive characteristics, BCS contains montmorillonite, which makes it incredibly susceptible to moisture-induced volume changes. When exposed to varying moisture levels, this soil exhibits severe shrink-swell behavior, leading to weak mechanical properties, low bearing capacity, and unequal differential settlement. For tall, dynamically loaded structures like transmission towers, this foundation instability often translates to diagonal structural cracking and severe vibration-

induced failures.

Therefore, improving the engineering properties of expansive soils—specifically by increasing strength and durability while decreasing consistency limits and swelling behavior—is a vital prerequisite for stable construction. Traditionally, soil stabilization utilizes additives that can be economically or environmentally taxing. However, repurposing recycled Construction and Demolition Waste (CDW)—such as crushed concrete, bricks, and mortar—has gained massive attention as an environmentally friendly, sustainable, and economical stabilization method. The demolition of older infrastructure generates a staggering amount of waste; for instance, India produces approximately 150 million tonnes of C&D waste annually. If improperly managed, this waste exacerbates environmental issues, including air pollution and landfill overflow. Fortunately, CDW is a potent source of aluminosilicates, making it an excellent precursor for alkali-activated geopolymer materials. By utilizing fine-grained CDW to improve geotechnical behavior, the construction industry can significantly reduce the excessive depletion of natural resources like sand while mitigating construction-related waste

generation. While previous research has explored the physical and mechanical properties of CDW primarily for road sub-base materials, a critical research gap remains in documenting the triaxial shear, consolidation, and micro-mineralogical behavior of geopolymer-stabilized soil specifically tailored for heavy building and tower foundations. The success of any stabilization technique relies heavily on rigorous laboratory testing to verify strength enhancements before field application. Addressing this gap, this study presents a comprehensive, dual-phase investigation. First, it examines the efficacy of blending C&D waste into BCS at varying percentages (5%, 10%, 15%, 20%, and 25%) activated by a sodium silicate and sodium hydroxide solution. Key parameters—including plasticity index, optimum moisture content, maximum dry density, and differential free swell index—are scrutinized, alongside advanced XRD microstructural analysis to verify the chemical transformation of the soil. Second, this paper bridges these micro-mineralogical soil improvements with macro-structural dynamics by evaluating the seismic response and base shear of a 40 m transmission tower with varying bracing patterns resting on this stabilized stratum. Through this comparative analysis, the study aims to provide an optimal, sustainable methodology that guarantees both foundational resilience and structural economy.

II. LITERATURE REVIEW

Global research emphasizes that expansive minerals like Montmorillonite must be chemically neutralized to ensure structural integrity. The utilization of recycled Construction and Demolition (C&D) wastes for soil stabilization demonstrates significant potential in mitigating the adverse effects of expansive soils. The addition of quarry dust to soft soils yields notable enhancements in swelling potential, shrinkage limits, compression, and durability, while also positively altering the sorptivity behavior of the treated soils. In the realm of construction waste management, a critical review highlights the imperative of reuse and recycling to mitigate pollution and reduce the environmental footprint of the construction industry. India generates approximately 150 million tonnes of C&D waste annually, yet only a minimal fraction (1%) is

recycled for high-value engineering use. Converting this waste into alkali-activated geopolymers provides a sustainable solution, creating Si-O-Al-O bonds that transform loose, expansive soil into a rigid, stone-like polymeric matrix. Reusing demolition waste is proven to reduce landfill pressure and lower overall construction costs for urban infrastructure. On the structural front, several investigators have studied the structural flexibility and optimization of transmission line towers by altering bracing parameters. Comparative studies indicate that angle section configurations are more efficient than square hollow sections, leading to reduced wind loads, lower foundation loads, and a decrease in overall tower weight. Analysis of different bracing systems reveals that single web horizontal and K-type bracings offer superior structural stability and less material consumption compared to Warren or X-bracing systems under lateral loading. Furthermore, finite element analysis underscores the importance of soil-structure interaction when evaluating the ultimate load capacity and failure patterns of these framed structures.

Significance of Present Study:

After a comprehensive review of the existing literature, the following gaps and problem statements were drawn:

- Lack of Integrated Geo-Structural Analysis: Limited research exists evaluating the direct dynamic structural response (e.g., base shear and modal time period) of highly loaded structures, such as transmission towers, resting specifically on geo-polymer-stabilized expansive soils.
- Gap in Micro-to-Macro Correlation: There is a lack of studies providing advanced micro-mineralogical verification (such as XRD analysis) that directly correlates the dissolution of expansive minerals to macro-structural safe bearing capacity calculations for foundations.
- Limited Research on Combined Optimization: While studies exist on either structural bracing or soil stabilization independently, there is a distinct lack of research focusing on holistic, end-to-end optimization combining both sustainable foundation amelioration (using C&D waste) and superstructure bracing efficiency.

- Lack of Documentation on Vibration Sensitivity: A critical gap exists regarding the triaxial shear behavior of geopolymer-stabilized soil tailored specifically to withstand dynamic environmental and structural vibrations.
- Insufficient Consolidation Data for Infrastructure: There are very few studies addressing the consolidation behavior and long-term settlement of geopolymer-stabilized soils designed specifically to support the massive loads of transmission infrastructure.

III. MATERIAL & METHODS

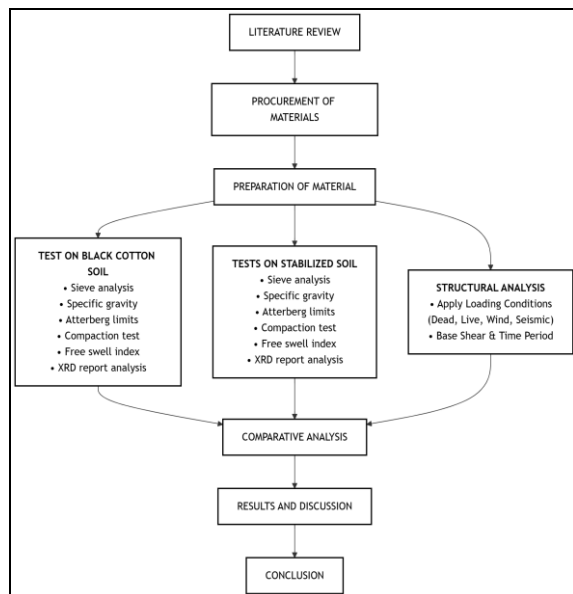


Fig -1: Flow-chart of methodology

Figure 1 presents the detailed methodology carried out in this research. Following the procurement of materials, preliminary geotechnical and micro-mineralogical tests were conducted on the native soil samples. This paper examines the stabilization of expansive black cotton soil using alkali-activated Construction and Demolition (C&D) waste, specifically recycled concrete, bricks, and mortar. Furthermore, the methodology outlines the parallel investigation of the structural dynamic response of transmission towers resting on this stabilized stratum, culminating in a comprehensive comparative analysis.

Figure- 2 : Trasmision Tower on BC-Soil

Figure 2 highlights the environmental challenges of erecting transmission towers on water-logged Black Cotton Soil. The soil's high montmorillonite content



causes extreme shrink-swell cycles that drastically reduce bearing capacity and risk foundation settlement. These adverse conditions demonstrate the critical need for the proposed C&D waste geopolymer stabilization to neutralize moisture effects and secure the tower's dynamic stability.



Figure 4: Constituents of C&D Wastes

Crushed C&D waste (<4.75 mm) was blended into the soil in 5% increments (from 5% to 25%) and tested in accordance with IS 2720 to determine the optimal percentage for stabilization.

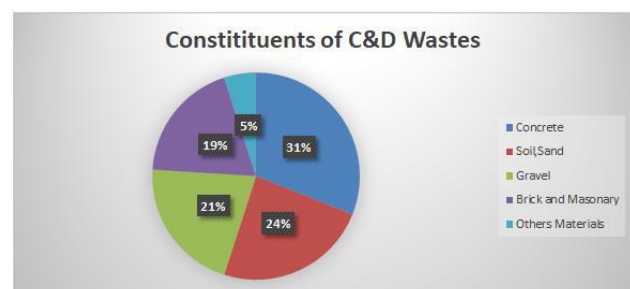


Figure 4: Constituents of C&D Wastes

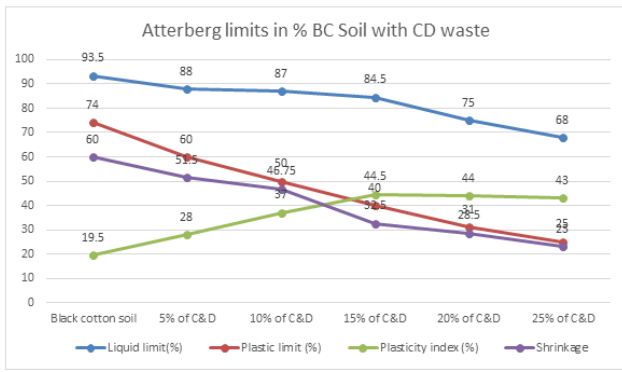


Figure 5: Consistency limits in % BC Soil with CD waste

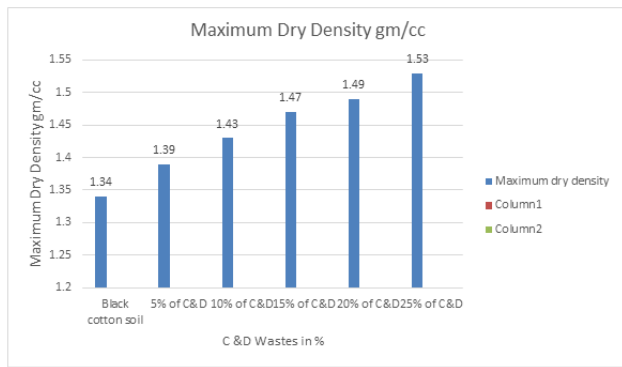


Figure 6: Maximum Dry Density with CD waste

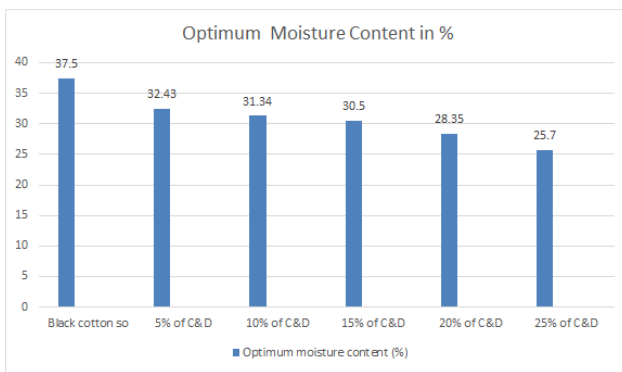


Figure 7: Optimum Moisture content with CD waste

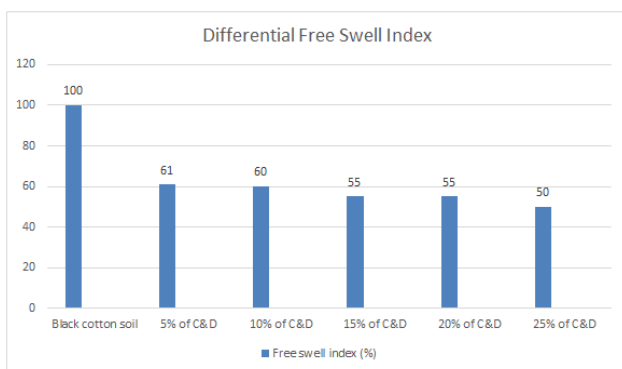


Figure 8: Differential Free Swell Index

IV. CONCLUSION

The primary purpose of this research was to enhance the engineering properties of expansive Black Cotton Soil (BCS), reduce its swelling potential, and subsequently evaluate the dynamic structural response of transmission line towers resting on this improved subgrade. Previous research has studied the effect of various traditional additives such as lime, rice husk ash, and cement kiln dust for soil stabilization, but many of these resulted in excessive heaving and infrastructure failures under heavy loads. The use of C&D wastes as a geopolymer soil stabilizer has been explored before, and the geotechnical results obtained in this research strongly align with successful prior studies, proving that C&D wastes can be highly effective foundation stabilizers.

In this study, improving the engineering properties of Black Cotton Soil with the addition of recycled C&D waste yielded the following results. Examining the incorporation of construction demolition waste at varying percentages (5%, 10%, 15%, 20%, and 25%) revealed substantial alterations in the material's key characteristics. The Liquid Limit exhibited a downward trend, declining from 88% to 68%, indicative of a reduced water content needed for plastic behavior. Concurrently, the Plastic Limit decreased from 60% to 25%, demonstrating enhanced resistance to deformation with increasing geopolymer content. This decline in Plastic Limit corresponded to an overall increase in the Plasticity Index, peaking at 44.5% with a 15% geopolymer addition before stabilizing around 43-44% with further increments. Moreover, the Shrinkage Limit diminished consistently from 51.5% to 23%, suggesting improved stability and minimized potential for volume change.

The Maximum Dry Density (MDD) of the soil exhibited a consistent increase with the addition of C&D wastes. Across the range of 5% to 25% C&D waste content, the MDD increased steadily from 1.39 g/cc to 1.53 g/cc. This trend indicates that the incorporation of C&D wastes positively influenced

the soil's density, creating a highly resilient structural matrix. Conversely, the Optimum Moisture Content (OMC) values of the soil varied inversely, dropping from 32.43% down to 25.70% as the waste content increased from 5% to 25%. Furthermore, the Differential Free Swell Index (FSI) dropped significantly from 100% to 61%, 60%, and eventually to 50% with the addition of 5%, 10%, 15%, 20%, and 25% C&D wastes, respectively.

Building upon this stabilized foundational stratum, the dynamic analysis of the 40m transmission tower revealed significant structural efficiencies. The Response Spectrum Analysis demonstrated that among the evaluated configurations, knee bracing provides the most optimal performance. The base shear for the knee-braced tower (22.641 KN) was notably lower than that of single bracing (27.623 KN) and double bracing (82.797 KN). Additionally, the knee bracing configuration yielded the lowest overall self-weight (847.743 KN) compared to the heavier double bracing (1382.742 KN), all while maintaining excellent dynamic time-period performance.

From the above observations, it is concluded that there is a significant improvement in the engineering properties of Black Cotton Soil when treated with geopolymer-activated C&D waste. Utilizing these wastes as a soil stabilizer presents a highly viable solution to address the foundational challenges associated with building heavily loaded transmission infrastructure. Moreover, it offers a means to mitigate the environmental repercussions stemming from extensive C&D waste generation, including land pollution and the depletion of landfill capacities. By combining this sustainable soil stabilization practice with an optimized, lightweight knee-braced tower design, overall project costs and material consumption are greatly minimized. This integrated approach ultimately contributes to environmental sustainability while guaranteeing the structural safety of vital lifeline infrastructure.

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