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Sustainable Stabilization of Expansive Black Cotton Soils Utilizing Industrial, Agricultural, and Municipal Solid Wastes A Comprehensive Review

Patil UD[1*], Patil VT[2], Bashire MB[3], Datar BK[4], Sangale DM[5], Shinde DB[6], Tonge RN[7]

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[1*] Udayram D. Patil, Faculty, Department of Civil Engineering, Government College of Engineering, Jalgaon, Maharashtra, India.
[2] Vilas T. Patil, Head, Department of Civil Engineering, Government College of Engineering, Jalgaon, Maharashtra, India.
[3] Manojkumar B. Bashire, Final Year B.Tech Student, Department of Civil Engineering, Government College of Engineering, Jalgaon, Maharashtra, India.
[4] Bhushan K. Datar, Final Year B.Tech Student, Department of Civil Engineering, Government College of Engineering, Jalgaon, Maharashtra, India.
[5] Darsh M. Sangale, Final Year B.Tech Student, Department of Civil Engineering, Government College of Engineering, Jalgaon, Maharashtra, India.
[6] Dnyaneshwar B. Shinde, Final Year B.Tech Student, Department of Civil Engineering, Government College of Engineering, Jalgaon, Maharashtra, India.
[7] Radhesham N. Tonge, Final Year B.Tech Student, Department of Civil Engineering, Government College of Engineering, Jalgaon, Maharashtra, India.

The stabilization of highly expansive Black Cotton Soil (BCS) presents a significant challenge in geotechnical engineering, primarily due to montmorillonite, a clay mineral that causes considerable volumetric instability with changes in moisture levels. This review examines recent literature on stabilization methods using industrial by-products, agricultural residues, polymeric reinforcements, and municipal solid wastes. Conventional chemical stabilizers such as Ordinary Portland Cement (OPC) and lime are increasingly viewed as environmentally harmful, costly, and unsustainable for large-scale infrastructure projects. This paper explores sustainable alternatives, including Waste Glass Powder (WGP), Construction and Demolition (C&D) waste, Sugarcane Bagasse Ash (SBA), Rice Husk Ash (RHA), Municipal Solid Waste Incineration (MSWI) ash, Eggshell Powder (ESP), industrial slags, and polymeric reinforcements like Polyethylene Terephthalate (PET) and glass fibers. By compiling experimental data, microstructural analyses, and predictive modeling techniques (such as Artificial Neural Networks and Multiple Linear Regression), this review identifies both consistencies and contradictions in material behaviors, especially in compaction characteristics, optimum moisture requirements, and shear strength. The results show that hybrid stabilization, combining pozzolanic wastes for chemical strength with fibrous/polymeric wastes for tensile flexibility, improves the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS). The review identifies existing research gaps, particularly the absence of dynamic cyclic loading data and thorough life-cycle energy assessments, and suggests future pathways to incorporate these eco-friendly subgrade treatments into standardized construction methodologies.

Keywords: Black Cotton Soil, Soil Stabilization, Waste Glass Powder, Waste

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1. Introduction

The swift increase in global urbanization and infrastructure development has led to a twofold crisis: the exhaustion of high-quality, structurally sound land and the rapid accumulation of industrial, agricultural, and municipal solid waste (Park, 2014). As a result, civil engineers are increasingly forced to construct foundations and highway pavements on challenging subgrades, particularly expansive soils. Black Cotton Soil (BCS) is an inorganic clay with medium to high compressibility, distinguished by a high concentration of the expansive clay mineral montmorillonite (Chen, 1988). This distinctive mineralogical makeup makes the soil extremely prone to significant swelling during moisture absorption in the wet season and considerable shrinkage along with deep desiccation cracking in dry periods (Garg, 2017). Such severe cyclic volumetric changes result in differential settlement, rutting, and catastrophic shear failure in the structures above, rendering native BCS entirely inappropriate for construction without thorough prior modification (Gromko, 1974).

Traditionally, the geotechnical field has heavily depended on chemical stabilization methods utilizing Ordinary Portland Cement (OPC) and lime. Although these calcium-based binders effectively trigger pozzolanic reactions that agglomerate clay particles and significantly enhance shear strength, their production is energy-intensive and contributes substantially to global anthropogenic carbon dioxide emissions (Dash & Hussain, 2012). Additionally, the rising costs of these raw materials make them economically impractical for extensive rural road networks and low-income housing developments (Gaw et al., 2011; Osinubi, 2013).

At the same time, the management of millions of tons of waste—including non-biodegradable plastics, electronic waste (e-waste), crushed glass, MSWI ash, and agricultural ashes—represents a significant ecological threat, overloading landfills and polluting local ecosystems (Aziz et al., 2011). Incorporating these waste materials into soil stabilization offers a concrete benefit: it creates a high-performance construction subgrade while supporting a circular, low-carbon waste management economy (Bandipally et al., 2025).

This review synthesizes research from different studies on BCS stabilization. By organizing the literature by material type, examining methodologies, and analyzing discrepancies in experimental results, this paper provides an evidence-based assessment of waste-based soil stabilization and identifies directions for future sustainable geotechnical engineering.

2. Literature Review / Thematic Review

The studies reviewed have been organized by the physical and chemical characteristics of the waste admixtures employed. The main classifications encompass siliceous/pozzolanic wastes, construction and industrial aggregates, polymeric/fibrous reinforcements, and agricultural/municipal ashes.

2.1 Theme 1: Siliceous and Pozzolanic Wastes (Glass and Ceramic)

Waste Glass Powder (WGP) has been extensively studied due to its significant amorphous silica (SiO_2) content, which generally surpasses 70-80%, rendering it a highly reactive pozzolan when finely ground (Ikara et al., 2015).

Multiple studies confirm that WGP modifies the consistency limits of BCS. Ibrahim et al. (2019) and Ashiq et al. (2022) showed that glass particles physically substitute for water-absorbent montmorillonite clay, reducing the plasticity index (PI) and linear shrinkage. Woldesenbet (2022) used kilned and powdered glass to lower the Free Swell Index (FSI) of expansive soil from 135% to 14%. Babatunde et al. (2019) and Benny et al. (2017) documented improvements in the UCS and CBR of highly expansive soils by minimizing moisture affinity.

Pure WGP often requires an alkaline activator to trigger effective cementation. Alelgn (2025) and Sheob et al. (2024) investigated minimal cement combined with WGP, showing that the calcium oxide in cement reacts with silica in the glass to produce Calcium-Silicate-Hydrate (C-S-H) gels. Hashmie et al. (2020) applied recycled glass powder through alkali activation (geopolymerization), finding that 9% dosage significantly enhanced unconfined compressive strength. Gouda et al. (2024) examined Ceramic Waste Powder (CWP) and found that when mixed with other ashes, ceramics' high hardness and resistance to physical degradation form a rigid subgrade matrix.

2.2 Theme 2: Construction, Demolition, and Industrial Dusts

The application of Construction and Demolition (C&D) waste, in conjunction with various industrial slags and dusts, primarily serves to enhance mechanical friction and reduce porosity.

C&D Waste and Concrete Aggregates: Dhananjaya et al. (2019) and Sandeep et al. (2025) noted that the incorporation of up to 15–25% pulverized C&D waste into BCS progressively decreases the Liquid Limit and Shrinkage Limit. The dense, granular characteristics of crushed concrete significantly elevate the Maximum Dry Density (MDD) from 1.35 g/cc to 1.55 g/cc while simultaneously lowering the Optimum Moisture Content (OMC) (Dhananjaya et al., 2019). Boraste (2026) supported these observations, indicating that the integration of C&D materials considerably reduces the required pavement thickness, thereby providing substantial cost savings and diverting materials from overloaded landfills.

Slags, Quarry Dust, and Foundry Sands: Ground Granulated Blast Furnace Slag (GGBS), copper slag, and iron ore tailings have been recognized as outstanding granular stabilizers. Prasad et al. (2019) and Nanda et al. (2016) combined GGBS with plastic fibers and lime, observing significant improvements in structural load-bearing capacity. Sarde (2018) effectively stabilized BCS using Waste Foundry Sand mixed with a commercial stabilizer (RBI Grade 81), increasing the CBR to 10.01%. Likewise, Anand et al. (2020) demonstrated that Quarry Dust, when utilized at levels exceeding 10% in conjunction with lime, markedly improves the structural characteristics of native clay. Ogundalu (2013) and Yohanna et al. (2019) confirmed the effectiveness of steel mill scale and iron ore tailings, respectively, showing that these heavy industrial by-products significantly enhance the dry density and internal friction of the composite matrix.

2.3 Theme 3: Polymeric, Plastic, and Fibrous Reinforcements

Unlike powders that modify soil chemistry, waste plastics and fibers primarily stabilize soils through mechanical interlocking and tensile reinforcement.

Waste Plastics and PET: Hoque et al. (2018), Ahalya & Prasad (2023), and Kumawat & Mathur (2020) show that Polyethylene Terephthalate (PET) plastic strips bridge micro-cracks and reduce brittle shear failure. Woldesenbet (2023) achieved an unsoaked CBR of 17.5% by combining 24% glass powder with 8% plastic strips, demonstrating that plastics provide the tensile ductility needed to offset brittleness in chemical binders. Niyomukiza et al. (2021) and Gaikwad (2024) validated recycled PET bottles, e-waste, and shredded single-use face masks as tensile inclusions.

Glass, Synthetic, and Natural Fibers: Singh et al. (2023) and Bhadoriya & Kansal (2018) examined micro-glass fibers. These lightweight, durable materials cross shear planes within the clay and increase the internal friction angle. Syed et al. (2019) found that alkali-activated binders combined with polypropylene fibers produce a ductile, high-strength composite subgrade. Natural fibers have also been tested; Vineel et al. (2020) and Arthi et al. (2017) showed that Coir Pith restrains soil swelling, while Zakikhani et al. (2005) and Ghosha et al. (2017) demonstrated that bamboo fibers and jute geotextiles work in low-income housing foundations. Advanced nanomaterials such as nano-MgO and epoxy resins are being researched to improve interfacial adhesion and thermal stability in composite materials (Darweesh & Munef, 2025; Bahlakeh et al., 2018).

2.4 Theme 4: Agricultural and Municipal Solid Wastes

Agricultural waste is abundant in organic silicas and calcium, providing cost-effective pozzolans for rural infrastructure, while municipal sludges facilitate significant waste diversion due to their volume.

Bagasse, Rice Husk, and Sawdust Ashes: Sugarcane Bagasse Ash (SBA) and Rice Husk Ash (RHA) have been thoroughly validated. Spehia et al. (2018), Talekar & Joshi (2022), and Oviya & Manikandan (2016) established that replacing 6% to 8% of soil with SBA/RHA results in optimal CBR enhancement before the porous ash begins to function as a weak filler. Obeta et al. (2019) and Otoko (2014) employed Sawdust Ash (SDA) in conjunction with lime, concluding that a ratio of 16% SDA to 4% lime effectively degrades expansive montmorillonite minerals over a curing period of 28 days.

Eggshell Powder and Paper Sludge: Anoop et al. (2009), Barazesh et al. (2012), and a comprehensive MSc Thesis (2020) assessed Eggshell Powder (ESP).

ESP serves as a direct, bio-derived source of calcium carbonate. When mixed with Waste Glass Powder, the calcium from the ESP activates the amorphous silica present in the glass, resulting in the formation of cementitious compounds that enhance the soil's dry density without industrial lime (MSc Thesis, 2020). Additionally, Patel et al. (2025) and Khalid et al. (2012) examined Waste Paper Sludge (WPS) ash, concluding that an optimal dosage of 8% doubles the UCS of weak soils.

MSWI Ash: Municipal Solid Waste Incineration (MSWI) ash serves as a binder. Randhawa & Chauhan (2021) and Baruah et al. (2020) conducted an extensive review of MSWI ash, highlighting its rich composition of calcium and silicon oxides, which enables it to replace expensive lime by as much as 75% in applications for subgrade stabilization.

3. Methodology of Reviewed Studies

The credibility of the stabilization improvements is determined by the experimental, microstructural, and numerical methodologies employed throughout the literature.

3.1 Experimental Frameworks

The studies examined consistently adhere to testing protocols dictated by ASTM, AASHTO, British Standards (BS 1377), or Indian Standard (IS 2720) codes. The foundational testing encompasses Specific Gravity, Atterberg limits, and Differential Free Swell Index (DFSI) (Ashiq et al., 2022; Punmia, 2011). Compaction properties are assessed through Standard Proctor (SP) and Modified Proctor (MP) tests. As noted by Moses & Osinubi (2013) and Ikara et al. (2015), applying the heavier Modified Proctor compactive effort on Bagasse Ash and cement-treated soil results in significantly higher Maximum Dry Density (MDD) and lower Optimum Moisture Content (OMC) compared to Standard Proctor, simulating the heavy vibratory rollers utilized in real-world construction. Strength metrics are established through Unconfined Compressive Strength (UCS) and Soaked/Unsoaked California Bearing Ratio (CBR) tests (Woldesenbet, 2023; Khatti et al., 2018).

3.2 Microstructural and Nanoscale Analysis

To demonstrate that chemical stabilization (rather than mere physical substitution) is taking place, researchers have employed Field Emission Scanning Electron Microscopy (FESEM), Energy Dispersive X-ray (EDX), and X-ray Diffraction (XRD). Singh et al. (2023) utilized FESEM to visually verify that glass fibers physically interlock with clay clusters. Woldesenbet (2022) employed XRD in conjunction with X'pert HighScore software to chart the mineralogical transition, confirming the complete elimination of expansive montmorillonite peaks (at Bragg's angle $2\theta = 28.5^\circ$) and the emergence of stable, non-expansive kaolinite and C-S-H structures following treatment. Moreover, advanced investigations by Darweesh & Munef (2025) and Tcherdyntsev (2021) used Atomic Force Microscopy (AFM) and nanoscale analyses to examine polymer-soil interfacial adhesion.

3.3 Advanced Numerical and Analytical Modeling

Moving beyond empirical laboratory testing, modern research uses advanced computational modeling techniques to forecast field behavior. Gouda et al. (2024) employed Plaxis 2D finite element software, applying the Mohr-Coulomb yield criterion. Their numerical simulation of a two-layer pavement system demonstrated that SBA and CWP treatments significantly reduce both horizontal and vertical strains under simulated traffic wheel loads.

Moreover, Ikara et al. (2019) implemented Multiple Linear Regression (MLR) to formulate mathematical equations that predict CBR based on OMC, MDD, and glass powder content, achieving a coefficient of determination (R^2) of 0.98. Advancing this concept, the MSc Thesis (2020) successfully constructed an Artificial Neural Network (ANN) model using MATLAB to forecast the CBR of ESP/WGP-stabilized soil. By assessing architectures such as the LOGSIG-PURELIN 5-6-1 network trained on empirical datasets, the model attained a correlation coefficient ($R^2 = 0.999$), offering a mathematical shortcut that replaces highly repetitive, time-consuming physical soaked CBR tests (MSc Thesis, 2020; Yildrim & Gunaydin, 2011). Lastly, macro-structural models, including those analyzing double-beam Timoshenko systems for tall buildings (Pinto-Cruz, 2025), depend on the premise of unyielding, stabilized foundation soils, underscoring the importance of the subgrade enhancements discussed herein.

4. Comparative Analysis

A thorough comparative analysis uncovers specific interactions within hybrid waste mixtures, while simultaneously highlighting contradictions in how individual waste materials affect soil mechanics.

4.1 Compaction Behavior: Density vs. Water Demand (The Porosity Paradox)

The most prevalent contradictions found in the literature relate to the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). The introduction of heavy, granular wastes such as Construction and Demolition (C&D) debris, Quarry Dust, or Iron Ore Tailings consistently results in an increase in MDD and a decrease in OMC, as these dense, non-absorbent aggregates effectively replace lighter, water-absorbing clay (Dhananjaya et al., 2019; Anand et al., 2020; Yohanna et al., 2021).

In contrast, the incorporation of agricultural ashes (including Bagasse Ash, Rice Husk Ash (RHA), and Sawdust) produces highly inconsistent outcomes. Spehia et al. (2018) and Saini et al. (2019) found that the MDD rises with the addition of Sawdust Ash (SBA) up to a threshold of 5%, beyond which it begins to decline. Conversely, Gabriel (2020) and Ikeagwuani et al. (2019) noted a continuous decrease in MDD and an increase in OMC from the initial addition of bagasse or palm kernel shell ash. This paradox arises from the specific gravity and cellular porosity of the ash. Lightweight, highly porous ashes absorb substantial quantities of water to facilitate lubrication during compaction, which elevates OMC and artificially reduces bulk density. Only when these ashes are combined with a heavier chemical binder (such as cement, lime, or Expanded Polystyrene (ESP)) does the structural matrix achieve proper densification (MSc Thesis, 2020; Mai-Bade et al., 2021).

4.2 Shear Strength and Reinforcement Mechanics (The Aspect Ratio Issue)

A significant contradiction arises concerning the influence of plastic strips and fibers on the internal friction of soil. While Hoque et al. (2018) and Kumawat & Mathur (2020) contend that plastics typically enhance load-bearing capacity by bridging micro-cracks, Ahalya & Prasad (2023) and Ingle (2021) highlight that improper geometries of plastic can indeed generate internal slip-planes. When plastic strips are excessively wide or exceed an optimal threshold (generally 4–8% by weight), they interfere with soil-to-soil grain contact, leading to a substantial decrease in the angle of internal friction (ϕ) and resulting in premature shear failure. Consequently, the effectiveness of fibrous reinforcement depends entirely on geometry.

4.3 The Pozzolanic Dependency of Siliceous Wastes

Another significant paradox pertains to the efficacy of Waste Glass Powder (WGP). Ashiq et al. (2022) documented substantial CBR improvements when utilizing WGP alone. Conversely, Jalal et al. (2022) and Ikara et al. (2015) discovered that pure glass provides minimal enhancements in soaked CBR. This inconsistency reveals a crucial oversight in testing: the alkaline dependency of amorphous silica. Glass powder is not intrinsically cementitious; it requires a highly alkaline environment ($pH > 10.5$) supplied by free calcium to dissolve the silica and produce stable C-S-H gels (Sheob et al., 2024; Dyer & Dhir, 2001). In cases where native BCS lacks sufficient calcium, pure WGP functions merely as an inert filler that is washed away during soaking. Therefore, WGP is only universally effective when combined with calcium donors such as lime, cement, or Eggshell Powder (MSc Thesis, 2020; Anoop et al., 2009).

4.4 Cost Efficiency and Sustainability

Despite mechanical contradictions, there exists a definitive consensus regarding economic and environmental factors. Bandipally et al. (2025) introduced an energy accounting framework that demonstrates WGP requires merely a fraction of the gigajoules per ton for crushing in comparison to the production of Portland cement, indicating an 80–85% decrease in embodied energy. When combined with recycled plastics or construction and demolition (C&D) waste, which incur no acquisition costs and effectively divert non-biodegradable materials from landfills, these hybrid waste mixtures offer significant economic potential for infrastructure development (Woldesenbet, 2023; Boraste, 2026; Maurya, 2022).

5. Research Gaps

In spite of the substantial body of research supporting the feasibility of waste-stabilized BCS, a thorough assessment reveals significant gaps that impede broad commercial standardization of these materials.

Lack of Long-Term Durability and Cyclic Loading Data: The majority of existing studies (Alelgn, 2025; Talekar & Joshi, 2022; Sarde, 2018) predominantly depend on short-term static tests (for instance, 7-to-28-day UCS and static CBR). In reality, highway subgrades are subjected to decades of dynamic traffic loads and recurrent weathering. The existing literature is largely lacking in cyclic triaxial testing to ascertain the dynamic resilient modulus, as well as standardized freeze-thaw and wet-dry durability assessments (according to ASTM D559) for soils stabilized with plastic or glass (Abdullah & Wahhab, 2019).

Methodological Weaknesses in Field-Scale Implementation: The findings primarily originate from perfectly uniform laboratory samples that are blended in small cylindrical molds. The challenges related to practical, real-world applicability—such as the uniform incorporation of fine glass powder or entangled plastic fibers into deep, saturated, highly cohesive clay beds using conventional rotary construction mixers—are seldom quantified (Woldesenbet, 2023; Boraste, 2026).

Chemical Variability in Municipal and Industrial Wastes: As highlighted by Randhawa & Chauhan (2021) and Gaikwad (2024), the chemical compositions of MSWI ash, e-waste, and even agricultural ashes vary significantly based on the source incinerator, combustion temperature, or batch. In the absence of universal chemical standardization or pre-testing protocols (for instance, mandatory X-ray Fluorescence profiling prior to use), civil engineers encounter substantial liability risks concerning structural unpredictability and the potential leaching of heavy metals into groundwater.

Table 1: Key Contradictions in the Stabilization of Black Cotton Soil.

Parameter	Material	Finding A (Source)	Finding B (Contradictory Source)
Internal Friction Angle (ϕ)	Waste Plastic Strips	Increased by 61.3% due to surface ribbing (Majji Gowri et al., 2018).	Reduced internal friction angle, but increased cohesion (Chebet et al., 2015).
Soaked CBR	Waste Glass Powder	Massive 300% increase at 20% dosage (Ashiq et al., 2022).	Increase is “very less, almost negligible” (Parihar et al., 2018).
Plastic Limit (PL)	Waste Glass Powder	Consistently decreases or remains constant (Ibrahim et al., 2019; Ikara et al., 2015).	Increases significantly by 39.52% at a 30% dosage (Lodha et al., 2021).
Maximum Dry Density (MDD)	Bagasse Ash / Fiber	Increases up to 5-6%, then decreases (Saini et al., 2019; Spehia et al., 2018).	Continuously falls from the first addition due to low specific gravity (Gabriel, 2012).
OMC Behavior	Poly-propylene Fibers	OMC does not show significant change (Durga Prasad et al.).	OMC significantly decreases as fiber repels water (Various).

6. Future Scope

To close the divide between laboratory achievements and global infrastructure application, research must focus on three areas.

1. Integration of Advanced Predictive AI and Machine Learning: Building on the foundations of Artificial Neural Networks established in the MSc Thesis (2020) and the regression models developed by Ikara et al. (2019), future investigations should implement deep learning algorithms trained on extensive global datasets. These models can rapidly optimize hybrid waste mix ratios (for example, balancing SBA porosity with WGP silica and ESP calcium) according to the specific index properties of the local native soil, serving as digital design twins for geotechnical engineers.
2. Full-Scale Field Trials and Dynamic Testing: Future geotechnical research must evolve from laboratory settings to full-scale test embankments. Treated subgrades should undergo cyclic triaxial testing to replicate millions of equivalent single axle loads (ESALs). Additionally, long-term environmental instrumentation using earth pressure cells and moisture sensors will track the durability of pozzolanic bonds created by MSWI ash and other binders in real-world scenarios.

3. Comprehensive Life-Cycle Assessment (LCA) and Energy Accounting: Following the framework proposed by Bandipally et al. (2025), Life Cycle Assessments must quantify carbon footprint reductions, embodied energy savings, and direct economic advantages. This data is necessary to persuade municipal authorities and transportation departments to amend paving regulations (such as IRC:37) to allow the incorporation of C&D and plastic waste in structural foundations.

7. Conclusion

The significant geotechnical risks associated with expansive Black Cotton Soil (BCS) have historically been addressed through the environmentally harmful and costly use of Portland cement and lime. Nevertheless, this review of 68 recent studies shows that industrial, agricultural, and municipal solid wastes offer effective, sustainable, and economically advantageous alternatives for soil stabilization.

The synthesized results indicate that siliceous materials such as Waste Glass Powder (WGP), Ceramic Waste, and Sugarcane Bagasse Ash (SBA) effectively initiate pozzolanic reactions when adequately activated by calcium-rich additives like Eggshell Powder (ESP) or minimal cement quantities. These chemical modifications significantly deteriorate the expansive montmorillonite minerals, leading to a substantial decrease in the soil's plasticity and Differential Free Swell Index (DFSI).

At the same time, the incorporation of Construction and Demolition (C&D) waste, Quarry Dust, Iron Ore Tailings, and recycled Polyethylene Terephthalate (PET) strips provides mechanical interlocking through physical tensile reinforcement. This combined strategy—merging chemical rigidification with physical reinforcement—addresses micro-cracks and enhances the Maximum Dry Density (MDD) and California Bearing Ratio (CBR) to standards appropriate for heavy highway subgrades.

The literature contains significant contradictions—especially concerning the differing moisture requirements of porous agricultural ashes compared to dense industrial slags, and the aspect-ratio dependency of plastic reinforcements. These can be addressed through meticulous geometric standardization and essential chemical profiling before stabilization.

Ultimately, by adopting advanced predictive modeling techniques (such as Artificial Neural Networks) and conducting comprehensive dynamic field testing, the geotechnical engineering sector can formulate standardized codes for waste utilization. This approach will lower global infrastructure expenses, divert millions of tons of hazardous waste from landfills, and support a sustainable, low-carbon construction industry.

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Conflict of Interest

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

Life Science Reporting

No life science threat was practiced in this research.

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