frontiers | Frontiers in Built Environment

TYPE Original Research
PUBLISHED 17 February 2026
DOI 10.3389/fbuil.2026.1746551

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RECEIVED 14 November 2025
REVISED 12 January 2026
ACCEPTED 15 January 2026
PUBLISHED 17 February 2026

CITATION
Kalita A, Omo Y, Paron O, Yangchin P and Paksok D (2026) Microstructural and strength analysis of lower Himalayan soil in Arunachal Pradesh using biomedical waste as additives. *Front. Built Environ.* 12:1746551.
doi: 10.3389/fbuil.2026.1746551

Microstructural and strength analysis of lower Himalayan soil in Arunachal Pradesh using biomedical waste as additives

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The escalating generation of biomedical waste poses critical environmental and health challenges globally. This study investigates the sustainable utilization of shredded nitrile gloves (NG) and Plaster of Paris (POP) as stabilizing additives for silty sand soil from the landslide-prone Nirjuli-Banderdewa corridor in Arunachal Pradesh, India. Comprehensive geotechnical characterization included compaction tests, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and advanced microstructural analysis using Scanning Electron Microscope (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). Nitrile gloves were incorporated at 0.35%, 0.5%, and 1% by dry weight, while POP was added at 3%, 6%, and 9%. Results demonstrated that the optimal combination of 0.5% NG and 6% POP achieved a 109% increase in UCS and more than doubled both soaked and unsoaked CBR values compared to untreated soil. Microstructural analysis revealed enhanced particle bonding, reduced porosity, and improved fabric integrity through bridging mechanisms and cementitious gel formation. The stabilized soil meets IRC specifications for heavily trafficked road subgrades, demonstrating a viable circular economy approach for biomedical waste management while addressing geotechnical challenges in the seismically active Himalayan region.

KEYWORDS

biomedical waste, California bearing ratio, energy dispersive X-ray spectroscopy, nitrile gloves, plaster of paris, scanning electron microscope, soil stabilization, unconfined compressive strength

1 Introduction

1.1 Regional context and geotechnical challenges

Arunachal Pradesh, situated in the Eastern Himalayan region of India, experiences unique geotechnical challenges due to its complex geological setting, high seismicity (Zone V), and monsoon-driven precipitation exceeding 2,500 mm annually (Kalita et al., 2021). The state's infrastructure development is constrained by widespread silty soils characterized by low bearing capacity, high compressibility, and susceptibility to landslides (Rehman and Azhoni, 2023; D. K. Singh et al., 2025). The Nirjuli-Banderdewa corridor, a critical transportation artery, traverses terrain dominated by silty sand deposits that exhibit poor engineering properties, including inadequate shear strength, high moisture sensitivity, and volume instability.

Conventional stabilization methods employing cement and lime are energy-intensive, contribute significantly to carbon emissions, and present economic challenges in remote Himalayan regions (Barbhuiya et al., 2025). This necessitates exploring sustainable alternatives using locally available or waste-derived materials that can simultaneously address soil improvement needs and waste management imperatives.

Recent research has increasingly focused on sustainable reuse of various waste streams in civil and geotechnical engineering to mitigate environmental impacts while enhancing soil performance. For example, Shinde et al. (2025) investigated the reuse of sterilized biomedical plastic waste, including face masks and gloves, in concrete pavement blocks, demonstrating acceptable mechanical performance and contributions to circular economy practices. Additionally, Brahmbhatt and Patel (2025) reported the integration of biomedical waste incineration ash with fly ash in concrete, indicating effective strength outcomes and environmental safety when waste ash is used as partial cement replacement.

Beyond biomedical waste specifically, the review by Khalid and Alshawmar (2024) provides a comprehensive analysis of recycled polyethylene terephthalate (PET) fibers and strips for soil stabilization, highlighting enhancements in shear strength, bearing capacity, and soil reinforcement potential, which are conceptually similar to polymeric reinforcement approaches explored in our study. Complementing this, Ravish et al. (2025) conducted a critical review of used polymers in soil stabilization, providing global insights into polymer-soil interactions relevant to the reinforcement mechanisms described in our work.

Despite these advances, systematic studies focusing on the direct reuse of sterilized biomedical waste for soil stabilization, particularly under challenging Himalayan geotechnical conditions, remain limited. Most existing investigations emphasize construction materials such as concrete or asphalt, while comparatively fewer studies address subgrade and foundation soils, where moisture sensitivity, seismic loading, and long-term durability are critical concerns. In addition, many studies lack detailed microstructural evidence linking waste-derived additives to macroscopic strength and bearing improvements, especially for silty sand soils prevalent in landslide-prone regions. In this context, the present study aims to bridge this research gap by evaluating the combined use of sterilized nitrile gloves and medical-grade Plaster of Paris as soil stabilizers for silty sand from the Nirjuli-Banderdewa corridor. By integrating comprehensive geotechnical testing with SEM and EDX-based microstructural analysis and assessing compliance with IRC subgrade requirements, the study contributes new insights into both the engineering performance and the sustainable management of biomedical waste within a circular economy framework tailored to the Lower Himalayan region.

1.2 Biomedical waste: a growing environmental challenge

Global biomedical waste generation has escalated dramatically, particularly following the COVID-19 pandemic, with India producing approximately 619 tons daily (Dehal et al., 2022). On an average, the hospital waste generation rate ranges from 0.5 to 2.0 kg/bed/day which amounts to about 0.33 million tons annually (Bhalla et al., 2019). Current disposal methods consisting of predominantly incineration and autoclaving are energy-intensive, generate greenhouse gases, and produce residual materials requiring further management (Zikhathile et al., 2022). NG constitute approximately 15%–20% of biomedical waste by weight and are non-biodegradable, persisting in landfills for decades (Prata et al., 2020).

FIGURE 1
Location of the soil sample collection.

POP (calcium sulfate hemihydrate), commonly used in orthopedic casts and dental applications, represents another significant component of medical waste. Upon discarding, POP casts are typically landfilled, despite their potential for beneficial reuse (Navale et al., 2019). The hydration properties of POP and its ability to form crystalline structures suggest potential applications in soil stabilization.

1.3 Research rationale and objectives

Recent studies have demonstrated the feasibility of incorporating waste materials including plastics, industrial by-products, and organic wastes into soil stabilization protocols (Haq et al., 2024; Wang et al., 2022; Zhu et al., 2022). However, systematic investigations combining biomedical waste derivatives with comprehensive microstructural characterization remain limited, particularly for Himalayan soils. This study addresses this knowledge gap through the following objectives:

- Evaluate the effects of shredded NG and POP on compaction characteristics, strength parameters, and bearing capacity of silty sand soil.
- Determine optimal additive dosages through systematic experimental design.
- Elucidate stabilization mechanisms through advanced microstructural analysis (SEM and EDX).
- Assess the suitability of stabilized soil for pavement subgrade applications according to IRC standards.
- Contribute to circular economic strategies for biomedical waste management.

TABLE 1 Geotechnical properties of silty sand.

Description	IS code	Values
Liquid limit	IS 2720-part V-1985 (Bureau of Indian Standards, 2006a)	25%
Plastic limit	IS 2720-part V-1985 (Bureau of Indian Standards, 2006a)	NIL
Plasticity index	IS 2720	25%
Specific gravity	IS: 2720-Part III-1980 (Bureau of Indian Standards, 2002)	2.5
Optimum moisture content	IS 2720 part VII-1980	14.7%
Maximum dry unit weight	IS 2720 part VII-1980	17.65 kN/m^3
Soil classification	IS classification	SM

2 Materials and methods

2.1 Soil characterization

Soil samples were collected from the Nirjuli-Banderdewa road section (27°05′N, 93°42′E) at a depth of 1.5–2.0 m below ground level (Figure 1). The sampling location was selected based on its history of pavement distress and documented slope instability (Rupa, 2015). Comprehensive geotechnical characterization was performed according to IS standards (Table 1). The soil was classified as silty sand (SM) as per the Unified Soil Classification System, with 47% sand, 52% silt, and 2% clay fractions (Table 2). Key properties included a liquid limit of 25%, plasticity index of 25%, specific gravity of 2.65, and maximum dry unit weight of 17.65 kN/m^3 at 14.7% optimum moisture content.

2.2 Biomedical waste materials

2.2.1 Nitrile gloves (NG)

Post-consumer nitrile examination gloves were collected from healthcare facilities in Nirjuli and sterilized using standard steam autoclaving at 121 °C and 15 psi for 30 min before mechanical shredding into 2–5 mm fragments (Figure 2). Autoclaving is a globally accepted and validated method for treating biomedical waste and has been proven to effectively inactivate bacteria, viruses, and spores under standard operating conditions, ensuring microbiological safety of polymer-based medical disposables. Previous studies have shown that steam sterilization at 121 °C for durations as short as 15 min achieves more than a 6-log reduction in microbial load, meeting international sterilization assurance levels for healthcare materials, and its reliability has been comprehensively documented in the literature (Rutala et al., 2023). This treatment method is also explicitly recommended by the World Health Organization and national biomedical waste management guidelines for contaminated plastic waste prior to reuse or recycling (Mcdonnell and Burke, 2011). Following sterilization, the nitrile gloves which are generally composed of an acrylonitrile-butadiene copolymer were shredded, and their inherent tensile strength and chemical resistance were expected to provide discrete reinforcement within the soil matrix, contributing to improved mechanical performance (Consoli et al., 2005).

TABLE 2 Grain size distribution of the soil.

Material		Grain size range (mm)	Percentage (%)
Sand (S)	Coarse sand	4.74 to 2.0	2.81
	Medium sand	2 to 0.425	9.73
	Fine sand	0.425 to 0.075	34.19
Silt (M)		0.075 to 0.002	52
Clay (C)		Less than 0.002	2

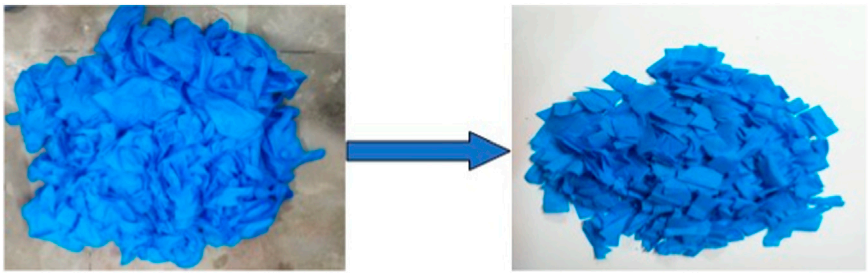


FIGURE 2
Nitrile gloves shredded into 2–5 mm fragments.

2.2.2 Plaster of Paris (POP)

Medical-grade calcium sulfate hemihydrate ($CaSO_4\cdot\frac{1}{2}H_2O$) was obtained from discarded orthopedic casts and mechanically cleaned to remove fabric liners and other contaminants. The material was then crushed, sieved through a 150-micron mesh, and thermally dried at 150 °C for at least 1 h, a process that significantly reduces any residual biological risk. X-ray fluorescence analysis confirmed CaO and SO_3 contents of 38.2% and 46.5%, respectively, consistent with medical-grade Plaster of Paris specifications (Singh and Garg, 2000). Previous studies have shown that calcium sulfate–based biomedical wastes pose negligible microbiological hazards after proper physical separation and thermal treatment, making them suitable for secondary reuse in construction and soil stabilization applications. In particular, Navale et al. (2019) demonstrated the safe reuse of biomedical POP waste following appropriate preprocessing, while Singh and Garg (2000) reported the chemical stability and environmental safety of waste gypsum and POP derivatives for civil engineering applications.

2.3 Experimental design and sample preparation

A systematic experimental matrix was designed to evaluate individual and combined effects of additives:

Series 1: Soil + NG (0.35%, 0.5%, 1.0% by dry weight).
Series 2: Soil + POP (3%, 6%, 9% by dry weight).
Series 3: Soil + NG + POP (all combinations).

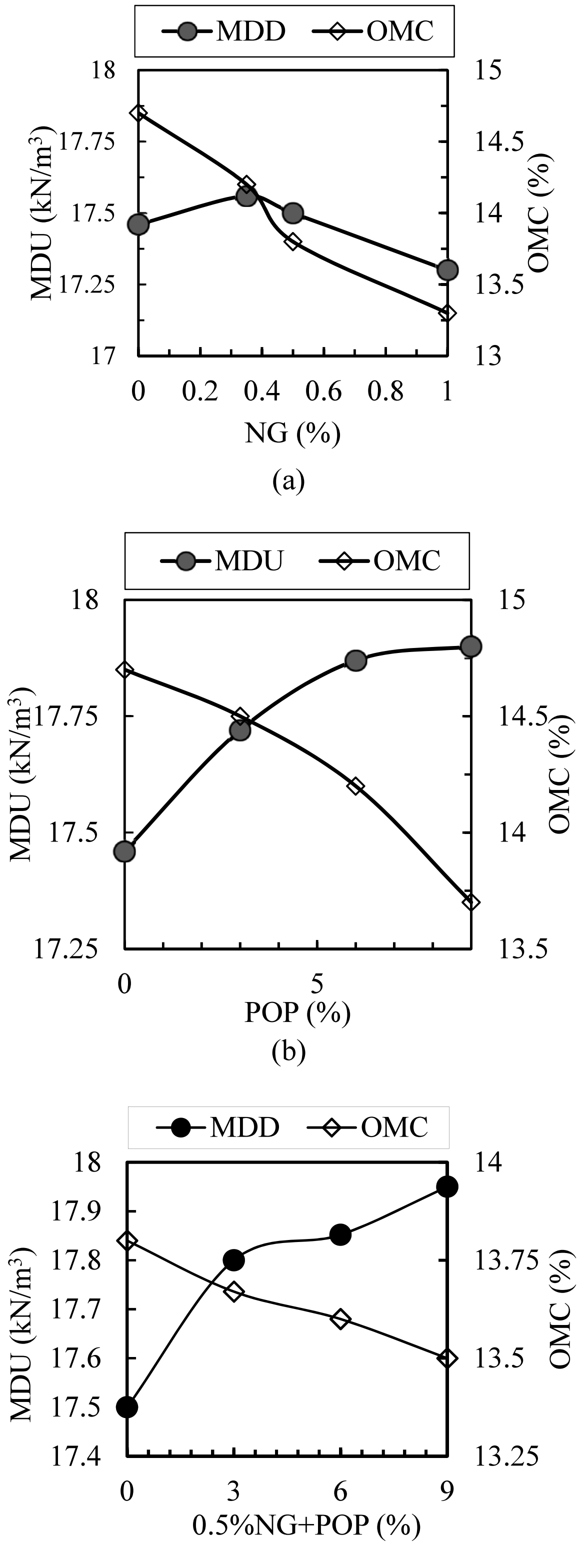
Soil was air-dried, pulverized, and sieved through a 4.75 mm sieve. Additives were incorporated through dry mixing for 10 min to ensure homogeneity, followed by moisture addition to achieve targeted water contents. Samples were compacted immediately to prevent premature hydration reactions.

2.4 Geotechnical testing

Compaction Tests: Standard Proctor compaction tests were performed as per IS 2720 (Part 7) to determine maximum dry unit weight (MDU) and optimum moisture content (OMC) for each mixture.

Unconfined Compressive Strength (UCS): Cylindrical specimens (38 mm diameter, 76 mm height) were prepared at OMC and MDU, sealed in plastic bags, and cured at 25 °C ± 2 °C under controlled humidity. Testing was conducted at 0, 7, 14, and 28 days of curing using a strain-controlled loading frame at 1.25 mm/min as per IS 2720 (Part 10) (IS:2720, 2011).

California Bearing Ratio (CBR): CBR tests were performed per IS 2720 (Part 16) (IS:2720, 2002) on specimens compacted in standard CBR moulds at OMC and MDU. Both soaked (96-h immersion) and unsoaked conditions were evaluated to assess moisture sensitivity. Penetration loads were recorded at 2.5 mm and 5.0 mm, with CBR values calculated relative to standard loads.



(a)

(b)

(c)

FIGURE 3
Variations of OMC and MDU for **(a)** Soil-nitrile mixes, **(b)** Soil-POP mixes, **(c)** 0.5% NG and varying POP content.

2.5 Microstructural analysis

The microstructure analysis of soil samples plays a crucial role in understanding the material's properties and behavior under various conditions. Scanning Electron Microscope (SEM) and Electron Dispersive X-ray (EDX) tests were conducted on a total of six samples, the soil, nitrile gloves, POP and the mixes with optimum values that are S+0.5%NG, S+6%POP and S+0.35% NG+9%POP.

3 Results and discussion

3.1 Compaction characteristics

3.1.1 Effect of nitrile gloves

Figure 3a illustrates the variation of MDU and OMC of silty sand soil with increasing percentages of shredded NG. The untreated soil exhibits an MDU of 17.46 kN/m^3 and an OMC of 14.7%. With the addition of 0.35% NG, the MDU increases to 17.56 kN/m^3, while the OMC decreases to 14.2%, indicating improved compaction efficiency. This behavior can be attributed to the flexible and thin nitrile fragments occupying interparticle voids, which enhances particle rearrangement and packing under compactive effort. At 0.5% NG content, the soil achieves a near-optimal MDU of 17.50 kN/m^3 with a further reduction in OMC to 13.8%. This suggests that an appropriate quantity of nitrile fibers promotes denser soil fabric by improving mechanical interlocking and reducing water demand due to the hydrophobic nature of nitrile polymers. However, at 1% NG content, the MDU decreases to 17.30 kN/m^3 despite continued reduction in OMC (13.3%). This reduction in dry unit weight is attributed to excess fiber content, which disrupts soil-to-soil contact, creates a more open structure, and increases internal voids, thereby limiting effective densification. Similar non-linear trends in compaction behavior have been reported for fiber-reinforced soils, where an optimum fiber content enhances packing efficiency, beyond which excessive fibers hinder compaction (Tang et al., 2007; Consoli et al., 2009a). These obesrvations indicate that shredded NG reduce moisture demand and marginally improve compaction characteristics at low dosages, with 0.35%–0.5% NG representing the optimum range for achieving favorable compaction behavior in silty sand soils.

3.1.2 Effect of plaster of Paris

The variation of MDU and OMC of silty sand soil with increasing POP content is observed in Figure 3b. With the addition of 3% POP, the MDU increases to 17.72 kN/m^3, accompanied by a slight reduction in OMC to 14.5%. This improvement is primarily attributed to the filler effect of fine POP particles, which occupy voids between soil grains and enhance particle packing under compactive effort. As the POP content increases to 6%, the MDU further rises to 17.87 kN/m^3, while the OMC decreases to 14.2%, indicating more efficient densification and reduced water demand. At this dosage, POP acts not only as a physical filler but also undergoes partial hydration, forming calcium sulfate dihydrate (gypsum), which improves interparticle bonding and soil fabric continuity. A further increase in POP content to 9% results in a marginal increase in MDU to 17.90 kN/m^3, while the OMC decreases more noticeably to 13.7%. The continued reduction in OMC is associated with water consumption during the hydration of calcium sulfate hemihydrate and the reduced affinity of the stabilized soil matrix for free water. However, the relatively small gain in MDU beyond 6% POP suggests that excess POP may lead to the formation of bulky hydration products and local agglomeration, which limits further improvement in packing efficiency. Similar trends have been reported in gypsum- and calcium-based soil stabilization studies, where an optimum additive content enhances density and reduces moisture demand, while excessive binder content yields diminishing returns in compaction performance (Nalbantoglu and Gucbilmez, 2001; Ren et al., 2022). These results indicate that POP significantly improves compaction characteristics of silty sand by increasing dry unit weight and lowering optimum moisture content, with 6%–9% POP identified as an effective range, and 6% representing the most efficient balance between densification and material utilization.

3.1.3 Combined effect

Figure 3c illustrates the variation of MDU and OMC of silty sand soil stabilized with a constant 0.5% shredded NG and varying POP contents. The soil amended with 0.5% NG alone exhibits an MDU of 17.50 kN/m^3 and an OMC of 13.80%, indicating that nitrile fibers marginally improve particle packing while reducing moisture demand due to their hydrophobic polymeric nature. With the addition of 3% POP, the MDU increases to 17.80 kN/m^3 and the OMC decreases to 13.67%, reflecting the combined effect of POP acting as a fine filler material and the flexible NG fragments promoting better particle rearrangement under compaction. As the POP content is increased to 6%, the MDU further rises to 17.85 kN/m^3, while the OMC reduces to 13.60%, suggesting enhanced densification resulting from void filling by POP particles and partial hydration of calcium sulfate hemihydrate, which improves interparticle bonding and soil fabric continuity. At 9% POP, the MDU reaches its maximum value of 17.95 kN/m^3 with a corresponding minimum OMC of 13.50%. The continuous reduction in OMC with increasing POP content is attributed to water consumption during the hydration of POP to gypsum ($CaSO_4 \cdot 2H_2O$) and the formation of a denser, less water-absorptive soil matrix. The progressive increase in MDU demonstrates a synergistic stabilization mechanism, where NG provides discrete reinforcement and flexibility, while POP contributes to binding and pore refinement. However, the relatively smaller increment in MDU beyond 6% POP suggests diminishing compaction efficiency gains, likely due to the formation of bulky hydration products that limit further improvement in packing density. Similar synergistic trends between fibers and calcium-based binders have been reported in stabilized soils, where an optimal combination enhances compaction and reduces moisture sensitivity more effectively than individual additives (Consoli et al., 2009a; Nalbantoglu and Gucbilmez, 2001; Ren et al., 2022). These results indicate that the combined use of 0.5% NG with 6%–9% POP significantly improves compaction characteristics of silty sand, with 0.5% NG + 6% POP representing an efficient and practical optimum when both densification and material economy are considered.

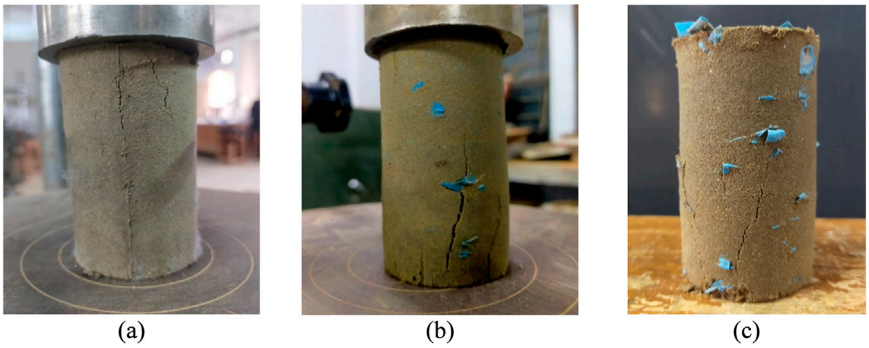


FIGURE 4
UCS test specimens for **(a)** soil, **(c)** Soil with nitrile gloves, **(c)** Soil with nitrile gloves and POP.

3.2 Unconfined compressive strength

3.2.1 Strength development in nitrile gloves-stabilized soil

Figures 4a–c shows the UCS test specimens for soil, Soil with nitrile gloves, Soil with nitrile gloves and POP. The stress-strain curve of plain soil is shown in Figure 5a. Plain soil exhibited minimal strength gain with curing, increasing from 70 kPa (0 days) to 93.6 kPa (28 days), reflecting limited cementation in natural silty sand. Nitrile gloves addition significantly enhanced both initial and long-term strength as shown in Figures 5b–d. For a NG content of 0.5%, the UCS after 28 days of curing reached 241.9 kPa (Figure 5c), indicating a substantial enhancement of 158% relative to the untreated soil.

The strengthening mechanism involves discrete reinforcement through stress transfer from soil matrix to tensile-resistant nitrile fragments, which bridge potential failure planes and provide post-peak ductility (Yetimoglu et al., 2005). However, at 1% NG, 28-day UCS decreased to 99 kPa (Figure 5d), indicating that excessive fiber content creates weak zones and reduces effective stress transmission (Michalowski and Čermák, 2003).

Figure 6a shows the UCS values of soil with various percentages of nitrile gloves at different curing periods. A substantial increase in the UCS values was observed at 0.5% NG content after 28 days of curing which can be attributed to the attainment of an optimum fiber dosage combined with the beneficial effects of extended curing duration. At this fiber content, nitrile gloves (NG) fibers are likely to be uniformly dispersed within the soil matrix, enabling effective stress transfer and improved soil-fiber interaction. Previous studies on fiber-reinforced soils have reported that an optimum fiber content enhances strength primarily through mechanical interlocking, frictional resistance, and the development of a reinforcing network within the soil structure (Tang et al., 2007; Consoli et al., 2002).

The significant increase in UCS at 28 days compared to the corresponding 14-day curing value for 0.5% NG suggests that curing time plays a critical role in mobilizing the reinforcing mechanism of fibers. Prolonged curing facilitates particle rearrangement, densification of the soil matrix, and improved interfacial bonding between fibers and soil particles, resulting in higher resistance to axial loading (Yetimoglu and Salbas, 2003; Estabragh et al., 2011). Similar strength gains have been reported in polymer and fiber-modified soils, where the reinforcing effect becomes more pronounced with time due to gradual enhancement of soil-fiber contact and frictional behavior (Correia et al., 2015). However, at a lower NG content of 0.35%, the fiber quantity may be insufficient to form a continuous reinforcing network, thereby limiting the contribution of fibers to strength development even at extended curing periods. Conversely, the reduction in UCS observed at higher NG content (1.0%) may be associated with fiber agglomeration and non-uniform distribution, leading to stress concentration and the formation of weak zones within the soil matrix, as widely reported in earlier studies (Consoli et al., 2009b). Therefore, the increase in UCS at 0.5% NG for 28-day curing represents an optimal balance between fiber content and curing duration, resulting in a substantial improvement in unconfined compressive strength.

3.2.2 Strength development in POP-Stabilized soil

POP addition produced significant strength improvements as shown in Figure 6b. At 6% POP, UCS increased from 156 kPa (0 days) to 352 kPa (28 days), representing a 109% gain over control soil. The increase in UCS values observed with the addition of Plaster of Paris (POP) can be attributed to its rapid hydration and subsequent formation of interlocking crystalline structures within the soil matrix. Upon mixing with water, POP (calcium sulfate hemihydrate) hydrates to form calcium sulfate dihydrate (gypsum), which acts as a binding agent between soil particles, leading to improved particle interlock and reduced pore spaces. This cementitious action enhances the stiffness and load-bearing capacity of the treated soil, resulting in higher UCS values with increasing POP content and curing time. Similar strength improvements due to gypsum-based and calcium-rich additives have been reported in stabilized soils, where the formation of cementitious bonds and crystalline networks significantly contributes to strength gain (Mahedi et al., 2020; Barman and Dash, 2022).

The progressive increase in UCS with curing duration indicates the time-dependent nature of hydration and crystallization processes, which promote densification and improved bonding at the soil–binder interface. The peak strength observed at 6% POP suggests an optimum binder content, beyond which further addition (9% POP) resulting in 251 kPa gave a comparatively lower strength

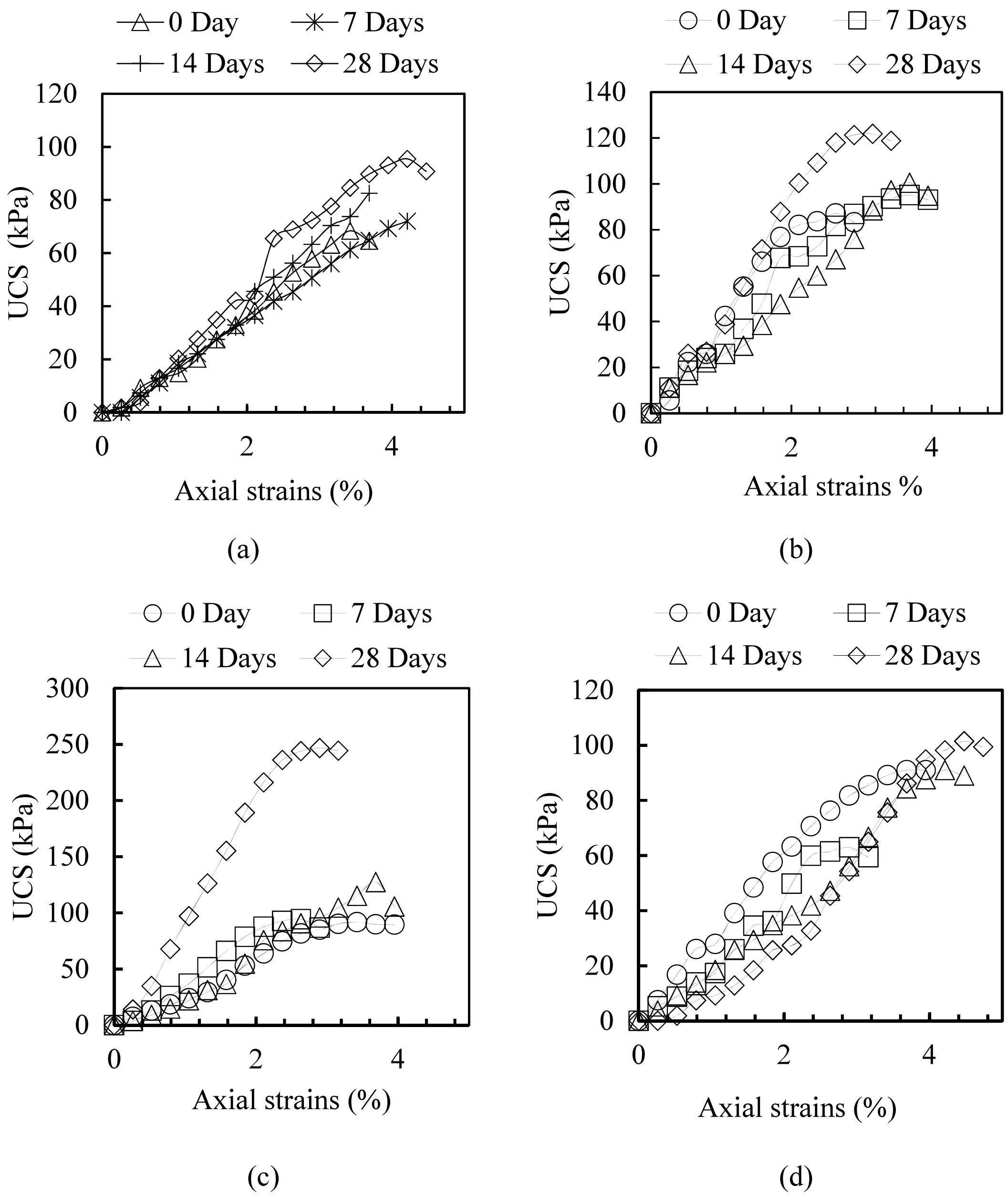


FIGURE 5
Stress strain curve at different curing periods of **(a)** plain soil, **(b)** soil+0.35%NG, **(c)** soil+0.5%NG, **(d)** soil+1%NG.

gain. This reduction may be associated with excess POP leading to incomplete bonding, increased brittleness, or the formation of weak planes due to unreacted material, as reported in earlier studies on chemically stabilized soils (Khemissa and Mahamedi, 2014; Seco et al., 2011; Sharma and Sivapullaiah, 2016). Overall, the observed UCS enhancement confirms the effectiveness of POP as a soil-stabilizing agent when used at an optimum proportion and adequate curing duration.

Figures 7a–c demonstrates the non-linear relationship between POP content and strength, with 6% representing the inflection point. As reported by (Shen et al., 2019) the hydration of calcium sulfate hemihydrate produces interlocking gypsum crystals that bind soil particles through crystallization pressure and chemical bonding. Microstructural evidence presented in Section 3.4 confirms this mechanism.

3.2.3 Synergistic effects in combined stabilization

Figure 8 illustrates the variation in unconfined compressive strength (UCS) of soil stabilized with combined additions of nitrile gloves (NG) fibers and Plaster of Paris (POP) at different curing periods. For soil containing 0.35% NG (Figure 8a), UCS increases progressively with increasing POP content and curing time, indicating that the cementitious hydration of POP, coupled with fiber-induced reinforcement, enhances particle bonding and stress transfer. A similar trend is observed for soil with 0.5% NG (Figure 8b), where a pronounced improvement in UCS is recorded

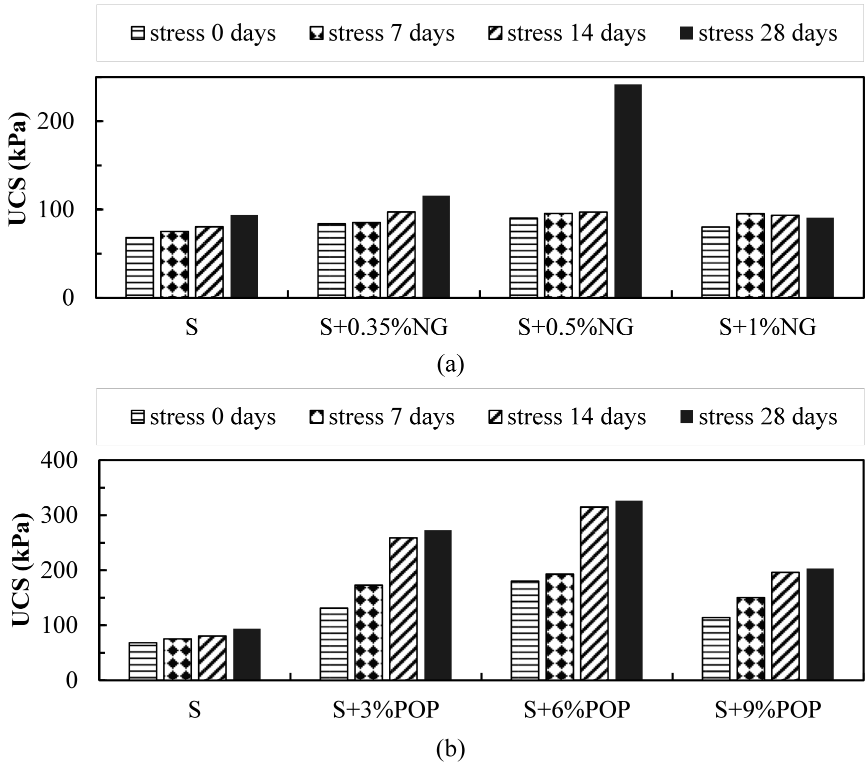


FIGURE 6
UCS values at different curing periods of **(a)** Soil with different percentages of NG, **(b)** Soil with different percentages of POP.

with increasing POP percentage, particularly at longer curing durations. This behavior suggests a synergistic effect between NG fibers and POP, wherein fibers provide tensile resistance and crack-bridging action, while POP contributes to strength gain through hydration and formation of calcium sulfate dihydrate crystals that bind soil particles. In the case of soil containing 1% NG (Figure 8c), although UCS improves with POP addition and curing, the rate of strength gain is comparatively lower, likely due to fiber agglomeration and non-uniform distribution at higher fiber contents, which may induce weak zones within the soil matrix. The overall results demonstrate that UCS enhancement is governed by an optimum combination of NG content, POP dosage, and curing duration, consistent with findings reported for fiber and binder-stabilized soils in previous studies (Yetimoglu and Salbas, 2003; Tang et al., 2007; Consoli et al., 2002). The observed time-dependent strength gain further confirms the role of curing in facilitating hydration, densification, and improved soil–binder–fiber interaction.

3.3 California Bearing Ratio

3.3.1 Effect of nitrile gloves and POP on the CBR of soil

Figures 9a–e illustrates the variation of California Bearing Ratio (CBR) values for untreated and treated soils under soaked and unsoaked conditions with varying contents of nitrile gloves (NG) fibers and Plaster of Paris (POP). As observed in Figure 9a, the CBR values initially increase with NG content and attain a peak at an intermediate dosage, beyond which a reduction is noted, indicating the presence of an optimum fiber content. This behavior is commonly attributed to enhanced interparticle friction, tensile resistance, and crack-bridging effects provided by randomly distributed fibers at lower dosages, while excessive fiber content leads to poor dispersion, fiber clustering, and reduced stress transfer efficiency (Yetimoglu and Salbas, 2003; Tang et al., 2007). Figure 9b shows that POP addition alone results in a moderate improvement in unsoaked CBR due to the formation of cementitious bonds arising from hydration and crystallization processes, however, soaked CBR values remain comparatively lower because moisture reduces matric suction and weakens interparticle bonding (Seco et al., 2011). Figures 9c–e demonstrate a significant enhancement in CBR when NG and POP are used in combination, particularly at intermediate POP contents, indicating a synergistic effect between fiber reinforcement and binder-induced cementation. The highest CBR values were observed for soil containing 0.5% NG with 6% POP, suggesting an optimum balance between tensile reinforcement from fibers and stiffness gain from POP hydration products. Although soaked CBR values are consistently lower than unsoaked values, the treated soils retain substantially higher bearing capacity compared to untreated soil, confirming the effectiveness of combined fiber-binder stabilization under both moisture conditions. Similar synergistic improvements in CBR have been widely reported for fiber and chemically stabilized soils in pavement applications (Estabragh et al., 2012; Sadek et al., 2010). The optimal combination (0.5% NG + 6% POP)

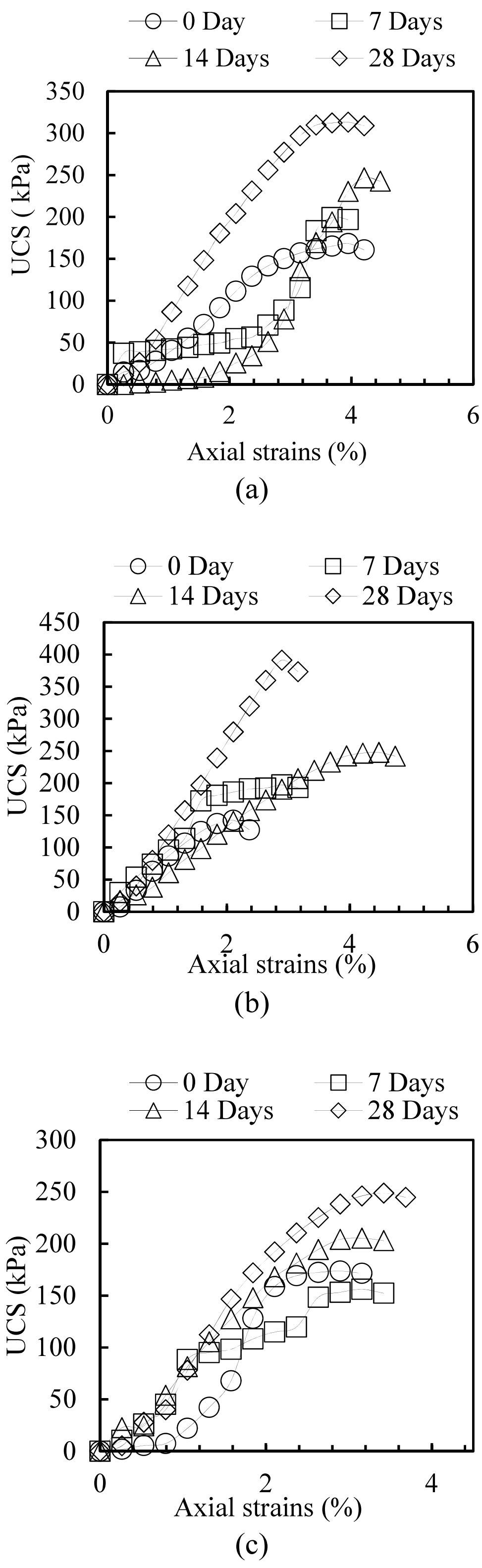


FIGURE 7
Stress strain curve of **(a)** soil+3%POP, **(b)** Soil+6%POP, **(c)** soil+9% POP, at different curing periods.

achieved unsoaked CBR of 29% and soaked CBR of 6.8%, representing 429% and 228% improvements over control soil, respectively. According to (IRC, 2018), these values qualify the stabilized soil for heavily trafficked road subgrades which requires a minimum soaked CBR of 5%.

3.4 Microstructural analysis

3.4.1 SEM observations

Scanning Electron Microscope analysis were performed on the plain soil, soil with 0.5% NG addition, soil with 6% POP addition and soil with NG and POP addition. For plain soil, SEM imaging of untreated soil (Figure 10a) revealed a loosely packed structure with angular to sub-angular particles, abundant macropores (10–50 µm), and minimal inter-particle bonding. The open fabric explains the low strength and high compressibility of natural silty sand. The SEM test of Soil +0.5% NG indicated that the addition of NG (Figure 10b) produced a more compact fabric with visible polymer fragments bridging soil particles. The flexible nitrile material conforms to particle surfaces, creating mechanical interlocking and reducing large voids. This bridging effect distributes applied stresses and inhibits crack propagation, consistent with observed strength improvements (Consoli et al., 1998). The SEM analysis of Soil +6% POP indicated that the POP-stabilized soil (Figure 10c) exhibited significant microstructural changes, including needle-like gypsum crystals (5–15 µm length) growing between soil particles, forming a three-dimensional network. Particle surfaces were coated with fine crystalline material, indicating chemical bonding. Porosity was visibly reduced through crystal growth filling voids. The interlocking gypsum structure provides mechanical strength and water resistance (Miller and Azad, 2000). The SEM imaging of Soil +0.35% NG + 9% POP showed that the combined stabilization (Figure 10d) demonstrated complementary mechanisms in which the nitrile fragments provide flexible reinforcement while gypsum crystals create rigid bonds. The resulting composite structure exhibits both strength and toughness, explaining superior performance in UCS and CBR tests.

3.4.2 EDX analysis

Energy-Dispersive X-ray (EDX) analysis of the plain soil, soil with 0.5% NG addition, soil with 6% POP addition and soil with NG and POP combination were performed to determine the elemental composition and chemical characteristics of the samples. For the plain soil (Figure 11a), elemental composition showed Si (32.1%), Al (8.7%), Fe (4.2%), Ca (2.1%), and O (48.3%), consistent with silicate mineralogy typical of Himalayan sediments (Garzanti et al., 2005). For Soil +0.5% NG (Figure 11b) the presence of N (2.8%) and elevated C (8.4%) confirmed nitrile incorporation. The acrylonitrile-butadiene structure contributes to tensile strength and chemical stability. For Soil +6% POP (Figure 11c) substantial increase in Ca (12.3%) and S (8.6%) verified gypsum formation. The Ca/S molar ratio of approximately 1.0 confirms $CaSO_4{\cdot}2H_2O$ stoichiometry. Reduction in porosity-related O (42.1%) indicates void filling by hydration products. For Soil +0.35% NG + 9% POP (Figure 11d) the combined spectra showed elevated Ca (14.8%), S (10.2%), N (1.9%), and C (6.7%), confirming presence of both stabilizers. The high Ca and S content correlates with superior strength and CBR values, validating the synergistic mechanism.

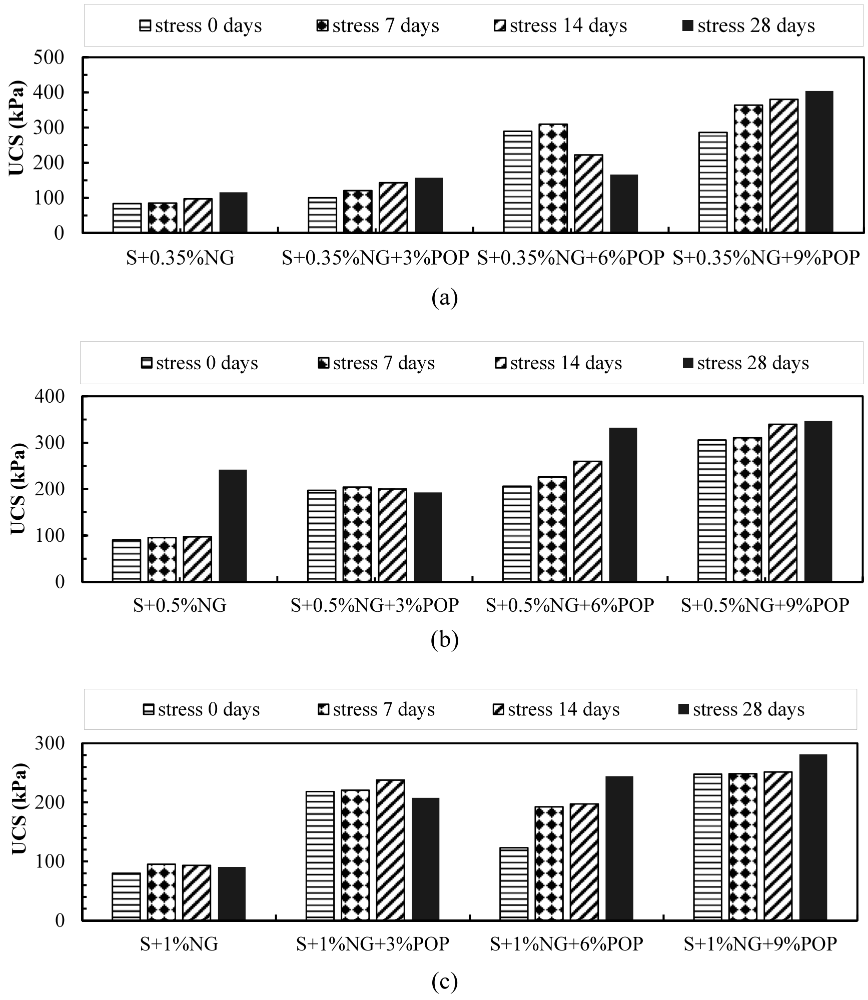


FIGURE 8
UCS values at different curing periods of **(a)** Soil with 0.35% of NG and different percentages of POP, **(b)** Soil with 0.5% of NG and different percentages of POP, **(c)** Soil with 1% NG and different percentages of POP.

4 Engineering implications and practical applications

4.1 Pavement subgrade suitability

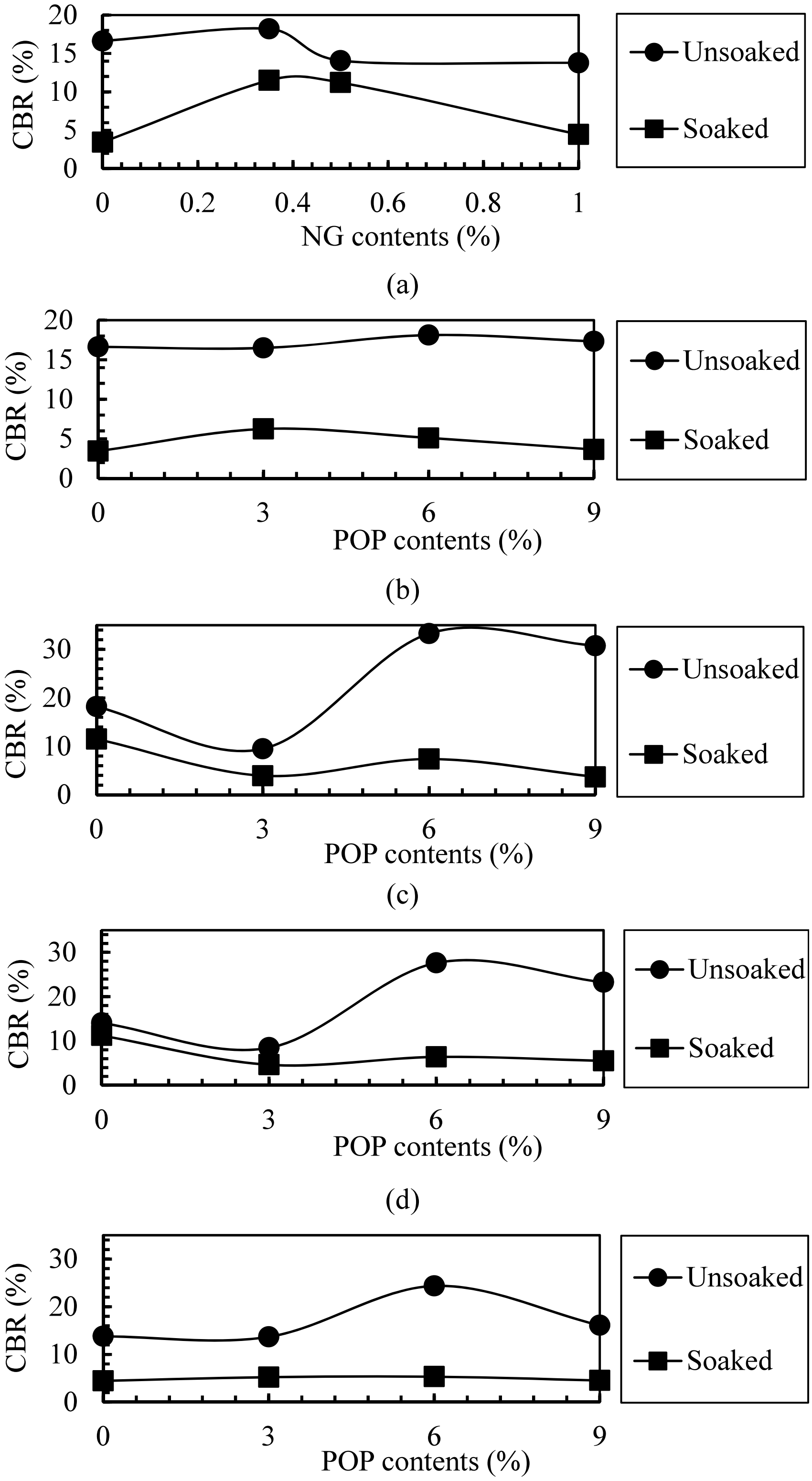
The stabilized soil meets IRC:37-2018 requirements for heavily trafficked flexible pavements (minimum soaked CBR of 5%) (IRC, 2018). The optimal mixture (0.5% NG + 6% POP) provides a safety factor of 1.36 relative to this threshold, accommodating variability in field conditions and long-term degradation. For the Nirjuli-Banderdewa corridor, implementation of this stabilization approach could reduce pavement layer thickness by approximately 150 mm, yielding significant cost savings (IRC, 2013).

4.2 Environmental and economic benefits

Stabilizing 1 km of road (7 m width, 0.5 m subgrade depth) requires approximately 2.6 tons of nitrile gloves and 31.5 tons of POP. This corresponds to annual biomedical waste generation from approximately 15 medium-sized hospitals, demonstrating scalable waste management potential (Somadas and Sarvade, 2024). Replacing 100 kg of cement with the NG-POP combination avoids approximately 90 kg of CO_2 emissions, contributing to climate change mitigation (Flower and Sanjayan, 2007). Life-cycle assessment is recommended for comprehensive environmental evaluation. Preliminary cost estimates suggest 25%–30% savings compared to conventional cement stabilization, primarily due to eliminated material costs for waste-derived additives. However, transportation and processing costs would require a proper site-specific evaluation.

4.3 Implementation considerations

Biomedical waste collection, segregation, sterilization, storage, and transfer are governed by mandatory regulatory frameworks, which require involvement of licensed healthcare facilities, authorized waste handlers, and documented treatment and traceability protocols. The reuse pathway investigated in this study is therefore based on the following essential assumptions: (i)



(a)

(b)

(c)

(d)

(e)

FIGURE 9
CBR values **(a)** Soil with different NG content, **(b)** Soil with different POP content, **(c)** Soil with 0.35%NG and different POP content, **(d)** Soil with 0.5% NG and different POP content, **(e)** Soil with 1%NG and different POP content.

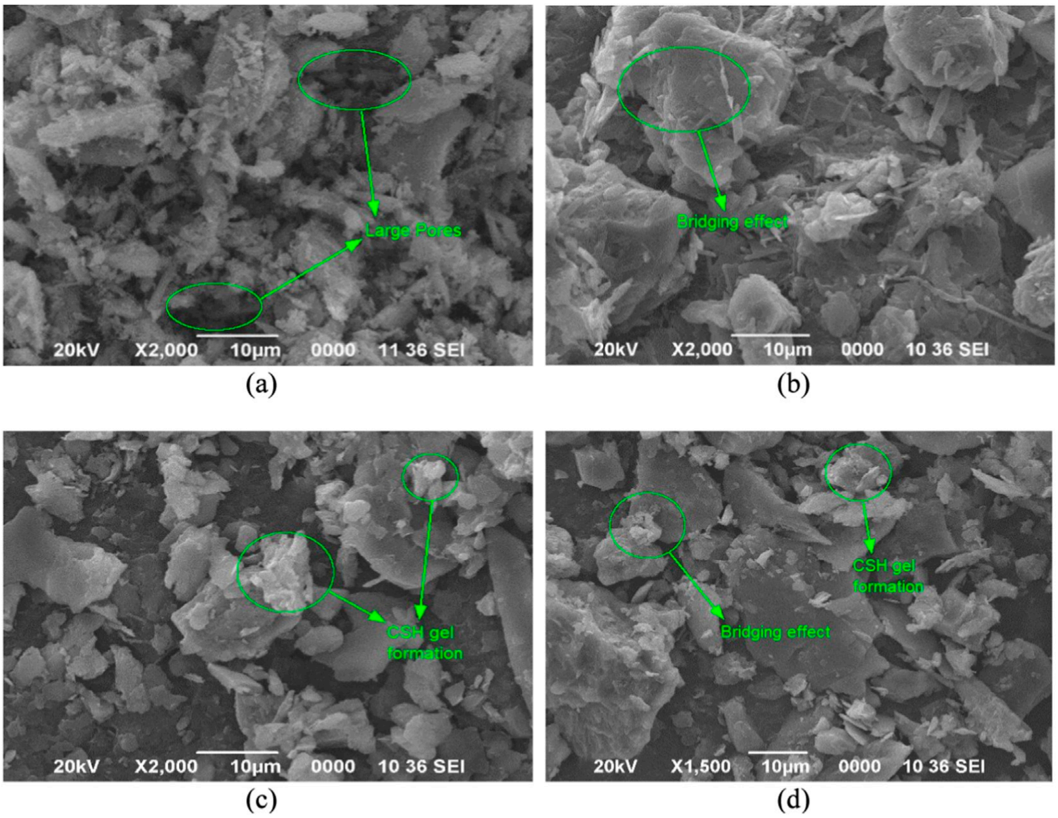


FIGURE 10
SEM image of **(a)** Soil, **(b)** S+0.5% NG, **(c)** S+6% POP, **(d)** S+0.35%NG+9%POP.

biomedical waste materials are sourced exclusively from authorized healthcare institutions; (ii) sterilization and preprocessing are completed prior to any material transfer for engineering use; and (iii) subsequent processing and utilization are conducted under institutional, municipal, or government-authorized oversight, rather than at the community or informal level. Moreover, similar regulated reuse models have already been successfully implemented and reported in the literature for biomedical waste ash, sterilized PPE plastics, and gypsum-based medical waste in civil engineering applications, without compromising public health or environmental safety (Wang et al., 2022; Somadas and Sarvade, 2024).

Building upon these demonstrated reuse practices, it is essential to address key practical considerations governing material consistency, long-term performance, and regulatory compliance to ensure safe and scalable field implementation:

Biomedical waste composition varies by source and sterilization method. Standardized protocols for material characterization, sterilization, and processing are essential for consistent performance (Al-Alawi et al., 2024).

While 28-day strength data are promising, field validation through accelerated durability testing (wet-dry, freeze-thaw cycles) and pilot-scale trials is recommended before widespread adoption (Said and Rahhal, 2022).

Implementation requires coordination with biomedical waste management authorities and compliance with environmental regulations. Leachability testing is advisable to ensure no mobilization of contaminants.

5 Conclusion

This study demonstrates the technical feasibility and environmental benefits of utilizing biomedical waste, specifically NG and POP, for stabilization of silty sand soil from the seismically active Lower Himalayan region of Arunachal Pradesh. Key findings include:

- The combination of 0.5% nitrile gloves and 6% Plaster of Paris by dry weight provides optimal performance, achieving 275% UCS improvement and more than twice the CBR values compared to untreated soil.
- The optimal mixture increases maximum dry unit weight by 7.3% and reduces optimum moisture content by 12%, facilitating field compaction and improving long-term stability.
- Time-resolved UCS testing revealed progressive strength gain over 28 days, attributed to gypsum crystallization and development of interlocking crystal networks. The stabilized soil exhibits both increased strength and improved toughness.
- Soaked CBR values of 6.8% exceed IRC:37-2018 requirements for heavily trafficked road subgrades, validating the suitability for pavement applications in the study region.
- SEM-EDX analysis elucidated dual mechanisms: (a) discrete reinforcement through nitrile fiber bridging, and (b) chemical bonding via gypsum crystal formation. The combined effect

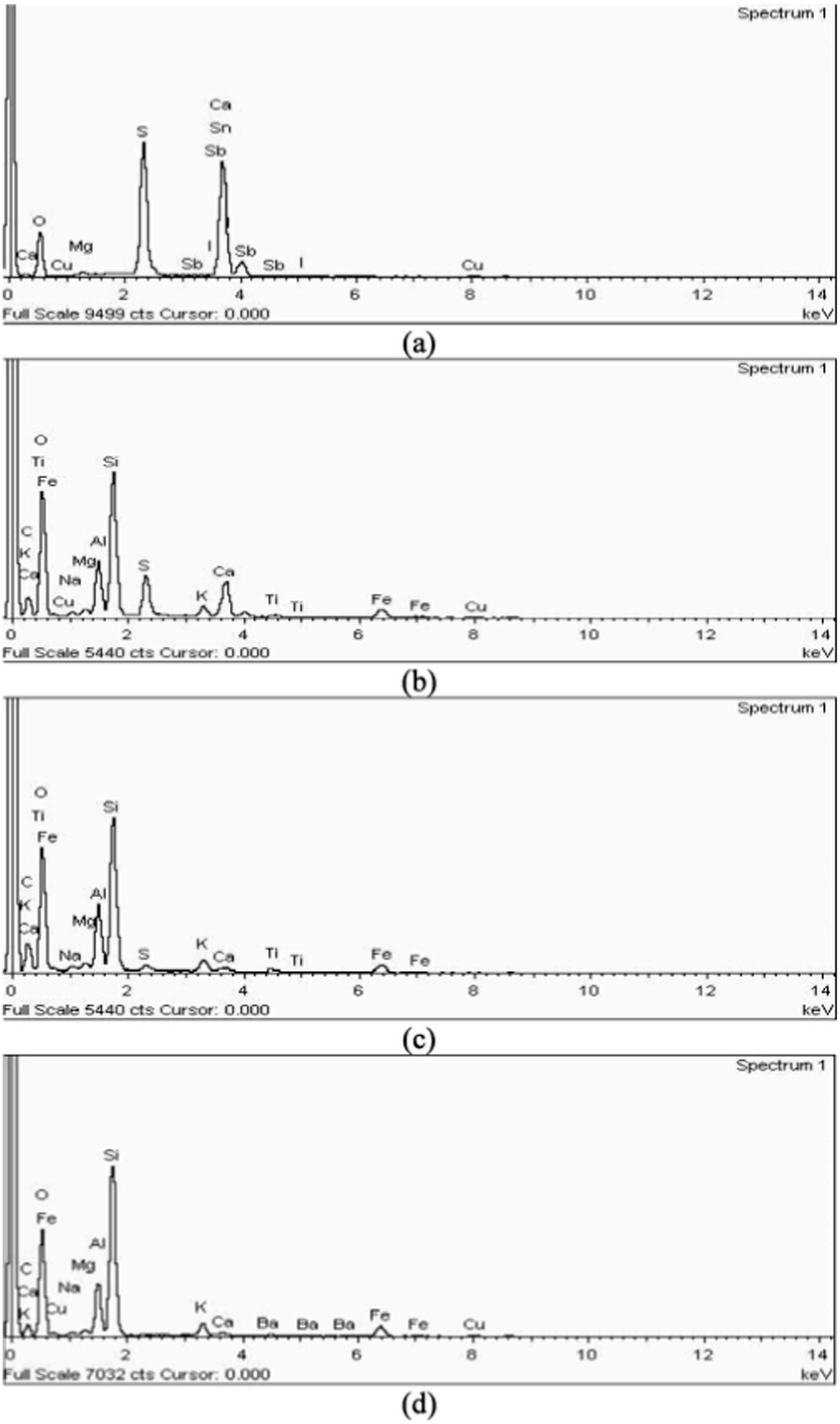


FIGURE 11
EDX result of **(a)** Soil, **(b)** (S+0.5%NG), **(c)** (S+6%POP), **(d)** (S+0.35%NG+9%POP).

produces a composite structure with enhanced fabric integrity and reduced porosity.
- This approach offers a circular economic solution for biomedical waste management while addressing critical geotechnical challenges in infrastructure development. Scalability analysis suggests significant waste diversion potential and reduced carbon emissions compared to conventional stabilization.
- For the landslide-prone Himalayan region, improved soil strength and moisture resistance contribute to slope stability and pavement longevity, addressing critical infrastructure resilience needs.

5.1 Future research directions

Long-term field performance monitoring, comprehensive environmental impact assessment including leachability testing, optimization for different soil types, and development of standardized protocols for biomedical waste processing and quality control are recommended to facilitate practical implementation.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AK: Supervision, Methodology, Conceptualization, Writing – review and editing, Writing – original draft. YO: Writing – review and editing, Formal Analysis, Methodology, Software. OP: Methodology, Writing – review and editing, Formal Analysis, Software. PY: Conceptualization, Writing – original draft, Data curation. DP: Data curation, Writing – original draft.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Acknowledgements

The authors acknowledge the Department of Civil Engineering, North Eastern Regional Institute of Science and Technology, for providing laboratory facilities. We thank the healthcare facilities in Nirjuli for providing biomedical waste materials and the Central Instrumentation Facility for SEM-EDX analysis.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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References

Al-Alawi, H. S. K., Al-Masqari, A. R. H., Chowdhury, M. S., Al Amri, A. K. A., and Umar, A. A. (2024). Stabilization of muscat's expansive soil using bottom ash from medical waste incineration. *E3S Web Conf.* 579, 02003. doi:10.1051/e3sconf/202457902003

Barbhuiya, S., Das, B. B., Adak, D., Kapoor, K., and Tabish, M. (2025). Low carbon concrete: advancements, challenges and future directions in sustainable construction. *Discov. Concr. Cem.* 1 (1), 1–24. doi:10.1007/s44416-025-00002-y

Barman, D., and Dash, S. K. (2022). Stabilization of expansive soils using chemical additives: a review. *J. Rock Mech. Geotechnical Eng.* 14 (4), 1319–1342. doi:10.1016/j.jrmge.2022.02.011

Bhalla, G. S., Bandyopadhyay, K., and Sahai, K. (2019). Keeping in pace with the new biomedical waste management rules: what we need to know. *Med. J. Armed Forces India* 75 (3), 240–245. doi:10.1016/j.mjafi.2018.12.003

Brahmbhatt, A., and Patel, B. (2025). Integrating biomedical and fly ash waste in concrete: a strength-based comparative study for sustainable construction. *Environ. Res. Technol.* 8 (4), 887–899. doi:10.35208/ert.1555389

Bureau of Indian Standards (2002). *Methods of test for aggregates, part 3: specific gravity, density, voids, absorption and bulking.* New Delhi, India: Bureau of Indian Standards. Available online at: https://law.resource.org/pub/in/bis/S03/is.2386.3.1963.pdf.

Bureau of Indian Standards (2006a). *Method of test for soils, part 5: determination of liquid limit and plastic limit of soil.* New Delhi, India: Bureau of Indian Standards. Available online at: https://law.resource.org/pub/in/bis/S03/is.2720.8.1983.pdf.

Bureau of Indian Standards (2006b). *Methods of test for soils, part 10: determination of unconfined compressive strength.* New Delhi: Bureau of Indian Standards. Available online at: https://law.resource.org/pub/in/bis/S03/is.2720.10.1991.pdf.

Consoli, N. C., Prietto, P. D., and Ulbrich, L. A. (1998). Influence of fiber and cement addition on behavior of sandy soil. *J. Geotechnical Geoenvironmental Eng.* 124 (12), 1211–1214. doi:10.1061/(ASCE)1090-0241(1998)124:12(1211)

Consoli, N. C., Montardo, J. P., Prietto, P. D. M., and Pasa, G. S. (2002). Engineering behavior of a sand reinforced with plastic waste. *J. Geotechnical Geoenvironmental Engineering* 128 (6), 462–472. doi:10.1061/(ASCE)1090-0241(2002)128:6(462)

Consoli, N. C., Casagrande, M. D., and Coop, M. R. (2005). Effect of fiber reinforcement on the isotropic compression behavior of a sand. *J. Geotechnical Geoenvironmental Eng.* 131 (11), 1434–1436. doi:10.1061/(ASCE)1090-0241(2005)131:11(1434)

Consoli, N. C., Vendruscolo, M. A., Fonini, A., and Dalla Rosa, F. (2009a). Fiber reinforcement effects on sand considering a wide cementation range. *Geotext. Geomembranes* 27 (3), 196–203. doi:10.1016/j.geotexmem.2008.11.005

Consoli, N. C., Festugato, L., and Heineck, K. S. (2009b). Strain-hardening behaviour of fibre-reinforced sand in view of filament geometry. *Geosynth. Int.* 16 (2), 109–115. doi:10.1680/gein.2009.16.2.109

Correia, A. A., Oliveira, P. J. V., and Custódio, D. G. (2015). Effect of polypropylene fibres on the compressive and tensile strength of a soft soil, artificially stabilised with binders. *Geotext. Geomembranes* 43 (2), 97–106. doi:10.1016/j.geotexmem.2014.11.008

Dehal, A., Vaidya, A. N., and Kumar, A. R. (2022). Biomedical waste generation and management during COVID-19 pandemic in India: challenges and possible management strategies. *Environ. Sci. Pollut. Res.* 29 (10), 14830–14845. doi:10.1007/s11356-021-16736-8

Estabragh, A. R., Bordbar, A. T., and Javadi, A. A. (2011). Mechanical behavior of a clay soil reinforced with nylon fibers. *Geotechnical Geol. Eng.* 29 (5), 899–908. doi:10.1007/s10706-011-9427-8

Estabragh, A. R., Namdar, P., and Javadi, A. A. (2012). Behavior of cement-stabilized clay reinforced with nylon fiber. *Geosynth. International* 19 (1), 85–92. doi:10.1680/gein.2012.19.1.85

Flower, D. J., and Sanjayan, J. G. (2007). Green house gas emissions due to concrete manufacture. *Int. J. Life Cycle Assess.* 12 (5), 282–288. doi:10.1065/lca2007.05.327

Garzanti, E., Vezzoli, G., Andò, S., Paparella, P., and Clift, P. D. (2005). Petrology of indus river sands: a key to interpret erosion history of the Western himalayan syntaxis. *Earth Planet. Sci. Lett.* 229 (3–4), 287–302. doi:10.1016/j.epsl.2004.11.008

Haq, M., Khan, M. A., Ali, S., Ali, K., Yusuf, M., Kamyab, H., et al. (2024). Enhancing clayey soil performance with lime and waste rubber tyre powder: mechanical, microstructural, and statistical analysis. *Environ. Res.* 256, 119217. doi:10.1016/j.envres.2024.119217

IRC (2013). Ministry of road transport and highways. Specifications for road and bridge works. Available online at: https://law.resource.org/pub/in/bis/irc/mort.250.2013.pdf.

IRC (2018). *37: 2018-guidelines for the design of flexible pavements*. New Delhi, India: IRC. Available online at: https://law.resource.org/pub/in/bis/irc/irc.gov.in.037.2019.pdf.

IS:2720 (2002). *Method of test for soils, part 16: laboratory determination of CBR*. Bureau of Indian Standards, Reaffirmed (New Delhi, India: Bureau of Indian Standards Manak Bhavan), 1–10. Available online at: https://dn790008.ca.archive.org/0/items/gov.in.is.2720.16.1987/is.2720.16.1987.pdf.

IS:2720 (2011). *Methods of test for soils, determination of water content dry density relation using light compaction*. Bureau of Indian Standards (New Delhi, India: Bureau of Indian Standards Manak Bhavan), 1–16. Available online at: https://dn790006.ca.archive.org/0/items/gov.in.is.2720.7.1980/is.2720.7.1980.pdf.

Kalita, A., Baruah, S., and Omo, Y. (2021). "Arunachal Pradesh," in *Geotechnical characteristics of soils and rocks of India* (London, United Kingdom: CRC Press), 37–55. doi:10.1201/9781003177159

Khalid, B., and Alshawmar, F. (2024). Comprehensive review of geotechnical engineering properties of recycled polyethylene terephthalate fibers and strips for soil stabilization. *Polymers* 16 (13), 1764. doi:10.3390/polym16131764

Khemissa, M., and Mahamedi, A. (2014). Cement and lime mixture stabilization of an expansive overconsolidated clay. *Appl. Clay Sci.* 95, 104–110. doi:10.1016/j.clay.2014.03.017

Mahedi, M., Cetin, B., and White, D. J. (2020). Cement, lime, and fly ashes in stabilizing expansive soils: performance evaluation and comparison. *J. Mater. Civ. Eng.* 32 (7), 04020177. doi:10.1061/(ASCE)MT.1943-5533.0003260

Mcdonnell, G., and Burke, P. (2011). Disinfection: is it time to reconsider spaulding. *J. Hosp. Infect.* 78 (3), 163–170. doi:10.1016/j.jhin.2011.05.002

Michalowski, R. L., and Čermák, J. (2003). Triaxial compression of sand reinforced with fibers. *J. Geotechnical Geoenvironmental Eng.* 129 (2), 125–136. doi:10.1061/(ASCE)1090-0241(2003)129:2(125)

Miller, G. A., and Azad, S. (2000). Influence of soil type on stabilization with cement kiln dust. *Constr. Build. Mater.* 14 (2), 89–97. doi:10.1016/S0950-0618(00)00007-6

Nalbantoglu, Z., and Gucbilmez, E. (2001). Improvement of calcareous expansive soils in semi-arid environments. *J. Arid Environ.* 47 (4), 453–463. doi:10.1006/jare.2000.0726

Navale, G., Gohil, K., Puppala, K., Shinde, S., Umbarkar, S., and Dharne, M. (2019). Rapid and greener method for utilization of plaster of paris (POP) waste generated from biomedical samples. *Int. J. Environ. Sci. Technol.* 16 (5), 2475–2480. doi:10.1007/s13762-018-2070-7

Prata, J. C., Silva, A. L., Walker, T. R., Duarte, A. C., and Rocha-Santos, T. (2020). COVID-19 pandemic repercussions on the use and management of plastics. *Environ. Sci. and Technol.* 54 (13), 7760–7765. doi:10.1021/acs.est.0c02178

Ravish, S., Puri, V., Kumari, A., Priya, A., Khan, A., and Singh, A. (2025). "A critical review of used polymers in the soil stabilization: the global experiences and future perspective," in *Sustainable infrastructures. EGRWSE 2023. Lecture notes in civil engineering*. Editors A. K. Agnihotri, K. R. Reddy, and A. Bansal (Singapore: Springer), 355, 105–117. doi:10.1007/978-981-97-8393-9_12

Rehman, S., and Azhoni, A. (2023). Analyzing landslide susceptibility, health vulnerability and risk using multi-criteria decision-making analysis in Arunachal Pradesh, India. *Acta Geophys.* 71 (1), 101–128. doi:10.1007/s11600-022-00943-z

Ren, H., Liu, W., and Zhang, D. (2022). Application of phosphogypsum to solidification of silty soil: mechanical properties and microstructure. *Mech. Adv. Mater. Struct.* 29 (27), 6026–6038. doi:10.1080/15376494.2021.1971804

Rupa, T. (2015). Geomorphological study with special reference to landslide in the adjoining areas of national highway no. 52-A (banderdewa to itanagar), Arunachal Pradesh. *IOSR J. Environ. Sci.* 9 (4), 20–26. doi:10.9790/2402-09432026

Rutala, W. A., Boyce, J. M., and Weber, D. J. (2023). Tag edFi ur tag edFi ur tag edH1 disinfection, sterilization and antisepsis: an overview tag edEn. AJIC. *Am. J. Infect. Control* 51 (11), A3–A12. doi:10.1016/j.ajic.2023.01.001

Sadek, S., Najjar, S. S., and Freiha, F. (2010). Shear strength of fiber-reinforced sands. *J. Geotechnical Geoenvironmental Engineering* 136 (3), 490–499. doi:10.1061/(ASCE)GT.1943-5606.0000235

Said, S., and Rahhal, M. E. (2022). Improving the compaction properties and shear resistance of a sand reinforced with COVID-19 waste mask fibers. *Heliyon* 8 (12), e12129. doi:10.1016/j.heliyon.2022.e12129

Seco, A., Ramírez, F., Miqueleiz, L., and García, B. J. A. C. S. (2011). Stabilization of expansive soils for use in construction. *Appl. Clay Science* 51 (3), 348–352. doi:10.1016/j.clay.2010.12.027

Sharma, A. K., and Sivapullaiah, P. V. (2016). Ground granulated blast furnace slag amended fly ash as an expansive soil stabilizer. *Soils Found.* 56 (2), 205–212. doi:10.1016/j.sandf.2016.02.004

Shen, Y., Wang, Y., Yang, Y., Sun, Q., Luo, T., and Zhang, H. (2019). Influence of surface roughness and hydrophilicity on bonding strength of concrete-rock interface. *Constr. Build. Mater.* 213, 156–166. doi:10.1016/j.conbuildmat.2019.04.078

Shinde, S. S., Bute, A. R., Gore, A. A., Khandale, P. R., Shingare, S. B., Kashid, S. G., et al. (2025). Sustainable utilization of biomedical waste in pavement blocks: a circular economy approach. *JournalNX* 11 (6), 26–31. Available online at: https://repo.journalnx.com/index.php/nx/article/view/5582.

Singh, M., and Garg, M. (2000). Making of anhydrite cement from waste gypsum. *Cem. Concr. Res.* 30 (4), 571–577. doi:10.1016/S0008-8846(00)00209-X

Singh, D. K., Verma, A. K., Verma, R. K., and Singh, T. N. (2025). Slope stability assessment of the section along balipara–charduar–tawang road, Arunachal Pradesh, India. *J. Earth Syst. Sci.* 134 (3), 137. doi:10.1007/s12040-025-02602-5

Somadas, P., and Sarvade, P. G. (2024). Sustainable engineering: utilisation of biomedical waste ash for untapped potential in soil stabilisation sustainable engineering: utilisation of biomedical waste ash for untapped potential in soil stabilisation. *Int. J. Sustain. Eng.* 17 (1), 1066–1082. doi:10.1080/19397038.2024.2434705

Tang, C., Shi, B., Gao, W., Chen, F., and Cai, Y. (2007). Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. *Geotext. Geomembranes* 25 (3), 194–202. doi:10.1016/j.geotexmem.2006.11.002

Wang, H., Guo, J., Liu, W., Song, H., Yan, T., and Fu, D. (2022). Use of COVID-19 personal protective equipment pollutants to improve physical properties of silty sand in yellow river flooded area. *Front. Environ. Sci.* 10 (September), 1–12. doi:10.3389/fenvs.2022.1011685

Yetimoglu, T., and Salbas, O. (2003). A study on shear strength of sands reinforced with randomly distributed discrete fibers. *Geotext. Geomembranes* 21 (2), 103–110. doi:10.1016/S0266-1144(03)00003-7

Yetimoglu, T., Inanir, M., and Inanir, O. E. (2005). A study on bearing capacity of randomly distributed fiber-reinforced sand fills overlying soft clay. *Geotext. Geomembranes* 23 (2), 174–183. doi:10.1016/j.geotexmem.2004.09.004

Zhu, J., Saberian, M., Perera, S. T. A. M., Roychand, R., Li, J., and Wang, G. (2022). Reusing COVID-19 disposable nitrile gloves to improve the mechanical properties of expansive clay subgrade: an innovative medical waste solution. *J. Clean. Prod.* 375, 134086. doi:10.1016/j.jclepro.2022.134086

Zikhathile, T., Atagana, H., Bwapwa, J., and Sawtell, D. (2022). A review of the impact that healthcare risk waste treatment technologies have on the environment. *Int. J. Environ. Res. Public Health* 19 (19), 11967. doi:10.3390/ijerph191911967