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INVESTIGATION OF CARBON NANO TUBE EFFECT ON SUBGRADE SOIL PROPERTIES

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Abstract

This study investigates the effectiveness of Multi-Walled Carbon Nanotubes (CNTs) in enhancing the geotechnical properties of weak subgrade soil for pavement applications. Poorly graded sand (SP) sourced from Naharlagun, Arunachal Pradesh, India, was treated with CNTs at 0.2%, 0.4%, and 0.6% by dry weight. A holistic evaluation of unconfined compressive strength (UCS), California Bearing Ratio (CBR), permeability, compaction, and shear strength was carried out marking the first comprehensive assessment of CNT-stabilized SP soil from Arunachal Pradesh. The results demonstrated substantial mechanical benefits, with UCS increasing by approximately 2.5-3 times after 28 days of curing at 0.6% CNT. CBR values also improved for both soaked and unsoaked conditions, indicating enhanced load-bearing capacity suitable for pavement layers. Additionally, a reduction of over 50% in permeability confirmed improved resistance to moisture ingress, which is essential for long-term subgrade performance in high-rainfall regions. Statistical analysis using ANOVA verified that the improvements in UCS and CBR were highly significant ($p < 0.001$), while compaction characteristics remained largely unchanged. These enhancements are attributed to nano-scale effects such as void filling and inter-particle bonding. Overall, CNTs show strong potential as a sustainable, low-dosage reinforcement material for moisture-sensitive subgrades in challenging terrains.

1.0 INTRODUCTION

The subgrade serves as the foundational layer of pavement systems, crucial for bearing traffic loads, maintaining structural stability, and ensuring long-term serviceability. A well-performing subgrade effectively dissipates stresses from repeated vehicular loads, thereby minimizing issues like rutting, deformation, and early surface failure [1] [2]. However, in high-rainfall regions and expansive soil zones, particularly those with silty or clayey formations, natural subgrades often exhibit low California Bearing Ratio (CBR), high plasticity, poor drainage, and moisture-driven volumetric changes, all of which significantly compromise pavement performance and longevity [3] [4].

To overcome these limitations, conventional soil stabilization methods typically use chemical additives such as cement, lime, and fly ash. These materials improve mechanical strength through pozzolanic reactions and enhanced particle bonding [5] [6].

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Nonetheless, such techniques face increasing scrutiny due to their environmental impact, lengthy curing times, and poor adaptability in sulphate-rich or waterlogged conditions where geochemical variability limits effectiveness [7] [8].

However, high-rainfall Himalayan regions such as Arunachal Pradesh present additional geotechnical challenges. The prevalent subgrade soils in these areas are often SP with low fines content, which leads to weak particle interlocking, high permeability, and rapid loss of strength upon wetting. [9]. Intense monsoon infiltration causes erosion, surface instability, and increased deformation under traffic loads [10] . Despite this, most existing CNT stabilization studies are focused on clay-dominant soils under controlled laboratory conditions, with limited attention to moisture-sensitive SP soils in complex mountainous environments [11]. Thus, a clear research gap exists in understanding how CNTs perform in reinforcing SP-type subgrade soils under field-like moisture exposure in the Eastern Himalayas. [12].

Despite these advantages, existing research has largely focused on clay-rich soils under ideal laboratory settings, with minimal investigation into CNT performance in silty sands or SP subgrades, particularly in moisture-sensitive, geologically active regions such as Arunachal Pradesh. Moreover, most studies examine individual parameters like UCS or CBR in isolation, lacking a holistic assessment of multiple geotechnical properties under a single experimental framework.

A comparative performance review (Table 1) highlights that MWCNTs consistently deliver superior strength gains and notable reductions in permeability, outperforming most other nanomaterials in both cohesive and cohesionless soils [13] [14] [15] .

Table 1: Comparative performance of CNTs with other nano materials

Nanomaterial	Soil Type Suitability	Strength Enhancement	Permeability Impact	Dispersion Challenge	Mechanism/Remarks
CNTs	Cohesive and cohesionless soils.	High (UCS & CBR ↑ 2–3×)	High (up to 56% ↓) [16], [17], [18]	High mechanical mixing needed.	Nano-bridging, void-filling, hydrophobic matrix
NS	Clayey/silty soils	High (UCS ↑ up to 150%)	Moderate. [19], [20]	Moderate	C-S-H gel formation, improved stiffness
NA	Clayey soils	Moderate to high	Moderate. [21]	High – agglomerates easily	Particle densification, thermal stability
NC	Expansive clays	Low to moderate	High [22], [23]	Low	Controls plasticity and shrink-swell
Nano-TiO_2	Silty/clayey soils	Low to moderate	Low to moderate. [24], [25]	Moderate	Photocatalytic, UV-reactive, minor strength benefit
Nano-$CaCO_3$	Silty and organic-rich soils	Moderate	Low to moderate. [26], [27], [28]	Low	Calcite precipitation improves stiffness
Nano-MgO	Clayey soils	Moderate	Moderate. [29]	Moderate	Enhances cohesion, reduces plasticity

This study explores the multi-functional performance of MWCNT-treated poorly graded sand (SP) subgrade soil from Naharlagun, Arunachal Pradesh, across varying CNT dosages and curing durations. Key geotechnical parameters including UCS, CBR, permeability, compaction, and shear strength are evaluated under both controlled and field-like moisture conditions. Statistical validation using ANOVA confirms significant improvements, especially in UCS and CBR ($p < 0.001$) [30]. The low dosage requirement highlights CNTs' potential for reducing material use and environmental impact [31] [32], while their electrical conductivity offers future

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possibilities for smart, self-monitoring pavement systems [33] [34].

CNT reinforcement of subgrade soil enhances performance through a series of physicochemical interactions that restructure the soil matrix. Well-dispersed CNTs bind with clay, sand, and silt particles, filling voids and increasing density through van der Waals, covalent, and electrostatic bonding mechanisms. This reinforced network improves load transfer, reduces pore connectivity, and enhances moisture resistance, resulting in significant gains in UCS, CBR, and permeability [35] [36].

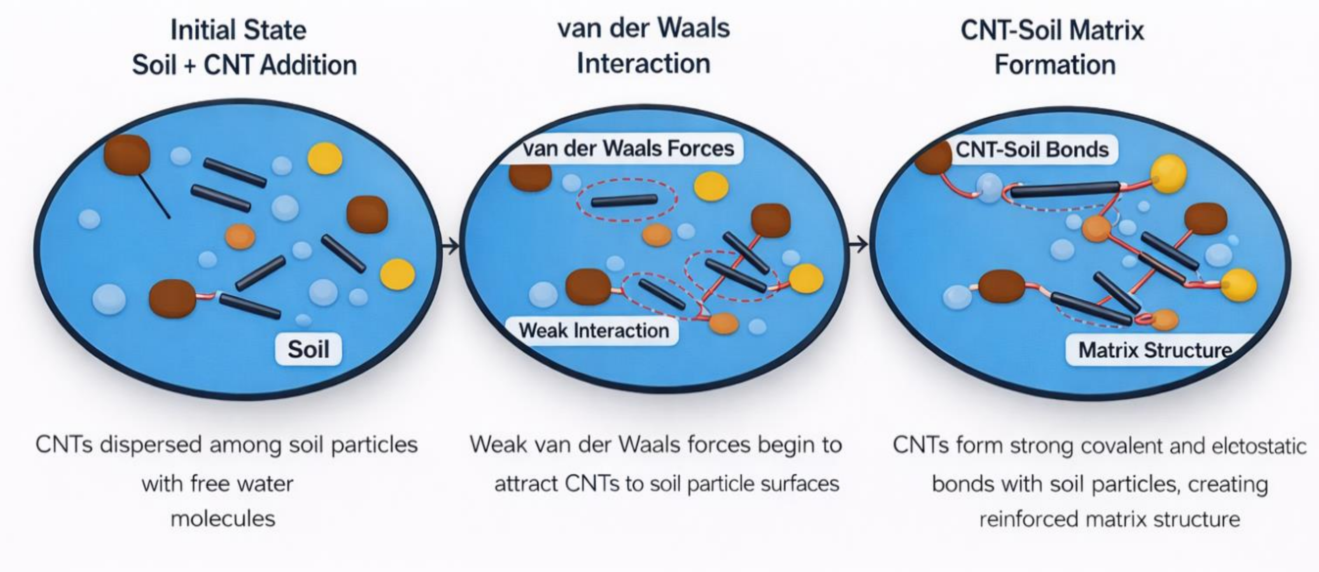

Figure 1: CNT-Soil interaction mechanism parameters. [37]

The objectives of this study are to investigate the effects of varying MWCNT dosages and curing durations on the mechanical and hydraulic performance of SP-type subgrade soil; to assess multiple geotechnical parameters UCS, CBR, permeability, compaction, and shear strength within a unified testing framework. For statistically validate the observed improvements using ANOVA and to evaluate the feasibility of CNT-based reinforcement as a sustainable, high-performance alternative to conventional stabilization methods in moisture-sensitive and geologically complex regions.

2.0 MATERIALS AND METHODS

2.1 Materials

2.1.1 Subgrade soil

The soil used in this study was sourced from a depth of 1.5-2.0 meters at a flyover construction site in Naharlagun, Arunachal Pradesh, India (27.1046° N, 93.6950° E). A region known for heavy rainfall and complex Eastern Himalayan geology. After air-drying, pulverization, and sieving through a 4.75 mm IS mesh, the soil was classified as poorly graded sand (SP) with low plasticity based on grain size and Atterberg limits (LL = 26.71%, Gs = 2.58) under the Indian Soil Classification System (ISCS) and a pH of 6.2 (slightly acidic) with a low organic content of 0.8%. Compaction testing yielded an Optimum Moisture Content (OMC) of 14.63% and a Maximum Dry Density (MDD) of 1.84 g/cm³. The untreated soil exhibited weak subgrade characteristics, with a UCS of 51.44 kN/m², a soaked CBR of just 5.56%, and high permeability (0.0768 cm/s), making it unsuitable for pavement layers without stabilization. These findings underscored the need for advanced reinforcement techniques to improve its geotechnical performance [38].

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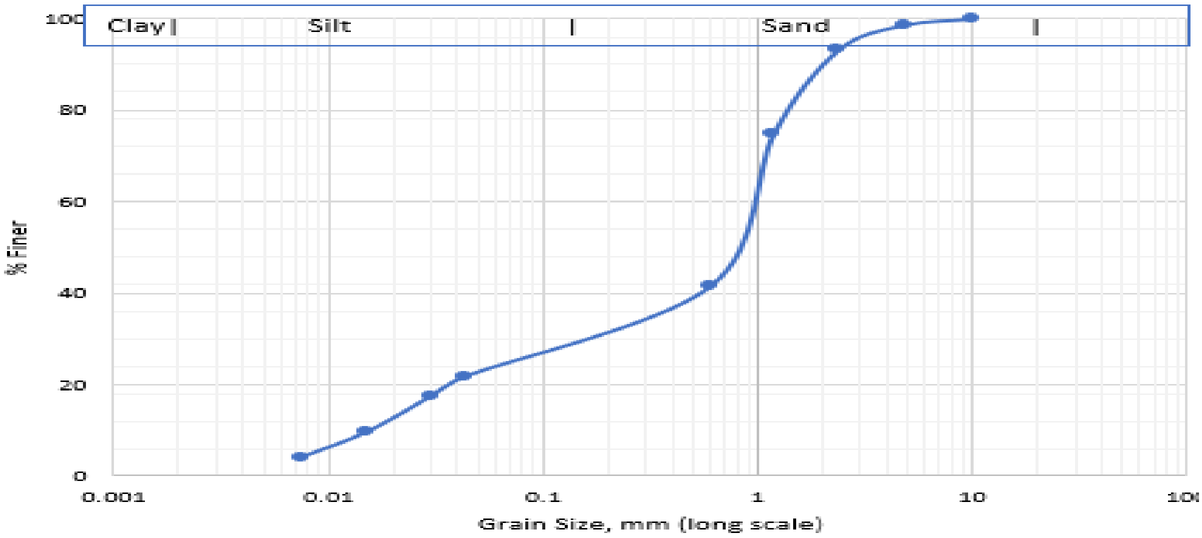

Figure 2: Particle size distribution curve of the untreated subgrade soil

2.1.2 Carbon nano tubes (CNTs)

MWCNTs were selected for soil stabilization due to their high mechanical strength, thermal stability, and large surface area, enabling strong interaction with soil particles. CNTs (95% purity; 10–20 nm outer diameter, up to 10 µm length, 233 m^2/g surface area) were added at 0.2%, 0.4%, and 0.6% by dry weight based on prior research [13][14]. This dosage range was selected as it is optimized to provide high strength gain while minimizing the cost associated with CNT use, based on literature that suggests 0.1%-0.6% is effective for soil stabilization. To ensure uniform dispersion. CNTs were stirred in distilled water and subjected to high-shear mechanical mixing (using an impeller at 1000 rpm for 30 minutes without surfactants to minimize agglomeration. This mixture was then mechanically blended with soil before moist curing for 7, 14, and 28 days, forming a reinforcing network that enhanced UCS, CBR, and reduced permeability. [17].

2.2 Methodology

2.2.1 Preparation of samples

In this study, CNT-treated soil samples were prepared using a controlled wet-mixing method to ensure uniform dispersion and consistent mechanical behaviour. Oven-dried and sieved subgrade soil was blended with 0.2%, 0.4%, and 0.6% MWCNTs dispersed in distilled water, then mixed mechanically for 10-15 minutes without surfactants to preserve native soil chemistry. The mixtures were compacted at optimum moisture content into standardized moulds, cured at 27 ± 2 °C for 7, 14, and 28 days, and subsequently tested for UCS, CBR, MDD, OMC, and permeability to evaluate performance enhancements.

Table 2: Physical properties of the CNTs

Property	**Value**
Type	MWCNTs
Outer Diameter	10-20 nm
Inner Diameter	5-10 nm
Length	Up to 10 µm
Specific Surface Area	~233 m^2/g
Density	~1.3-1.4 g/cm^3
Purity	>95%
Structure	Cylindrical (graphene-based)
Electrical Conductivity	~10^3-10^4 S/m (estimated)
Colour	Black
State/Form	Powder
Agglomeration Tendency	High (without dispersion aids)

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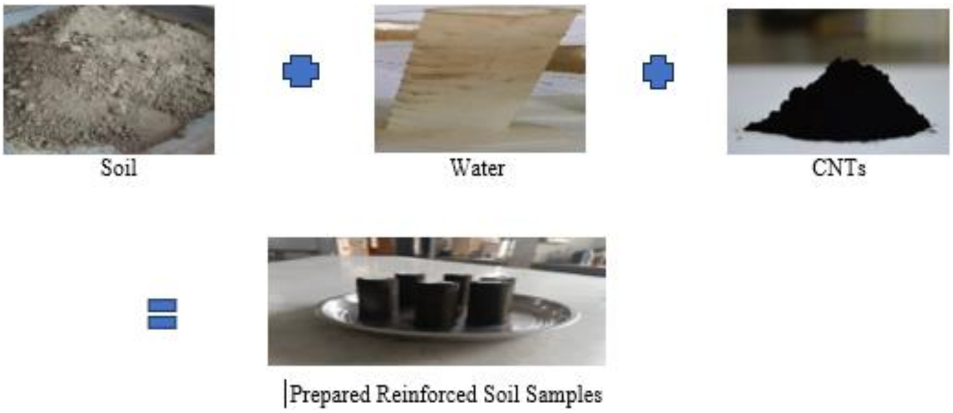

Figure 3: Samples of the prepared reinforced soil

Table 3: Reinforced soil samples of CNT-treated soil

Sample Code	**CNT Content (%)**	**Soil Type**	**LL (%)**	**PI (%)**	**Gs**	**OMC (%)**	CBR (%)	**MDD (g/cm³)**
CNT-0.0	0.00	SP	26.71	NP	2.58	14.63	5.56	**1.84**
CNT-0.2	0.20	SP	28.12	NP	2.56	14.77	21.64	**1.85**
CNT-0.4	0.40	SP	29.58	NP	2.56	15.06	25.24	**1.86**
CNT-0.6	0.60	SP	29.66	NP	2.55	15.27	27.05	**1.87**

2.3 Test Methods for the Subgrade Soil

The subgrade soil was tested using standard laboratory methods. Tests were performed as per relevant ASTM standards. The statistical robustness of the study was ensured by using three replicate samples {n=3} for all tests (UCS, Permeability, Shear Strength, and Atterberg Limits) and curing periods (0, 7, 14, 28 days). The CBR utilized two replicates {n=2} per condition, as detailed in the statistical analysis. All procedures were carried out under controlled conditions to ensure accuracy and consistency, and were discussed below-

2.3.1 Standard proctor compaction test

The compaction characteristics were determined as per IS 2720 Part 3, Sec 1 [39], by mixing soil with varying moisture contents, compacting in three layers using a 2.5 kg rammer, and deriving OMC and MDD from moisture-density curves.

2.3.2 California bearing ratio (CBR)

The CBR test, conducted as per IS 2720 Part 16 [40], involved compacting soil at OMC into standard moulds, soaking samples for 96 hours (where applicable), and measuring resistance to plunger penetration under soaked and unsoaked conditions to evaluate load-bearing capacity and moisture sensitivity

Figure 4: Prepared soaked and unsoaked CBR samples

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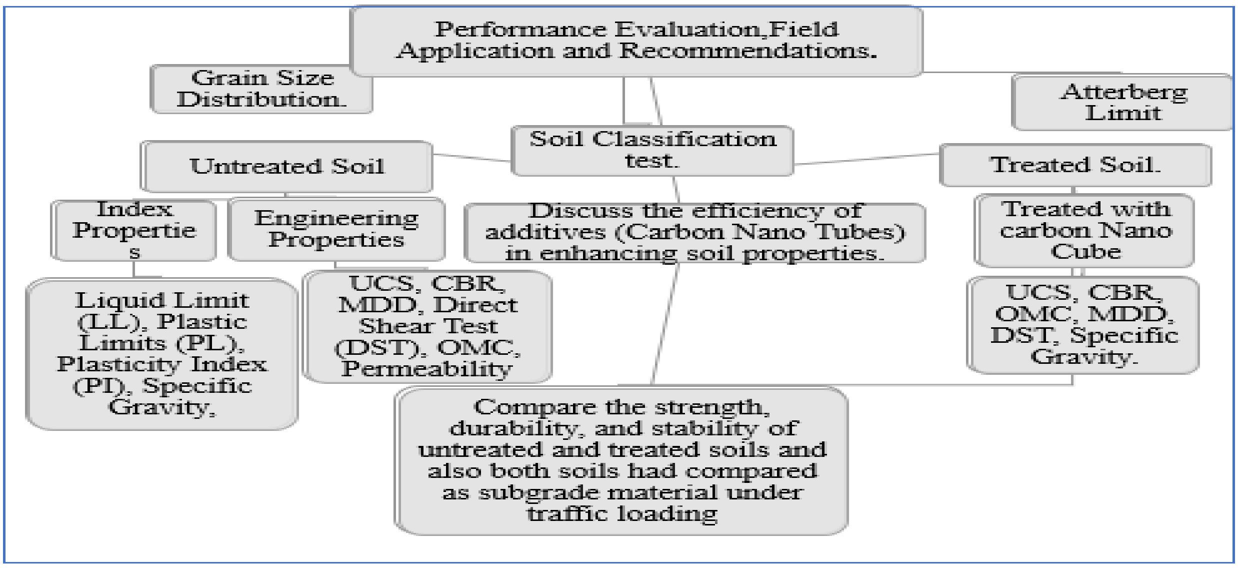

Figure *5*: Methodology flow chart of the study

2.3.3. Unconfined compression strength (UCS) test
The UCS of both untreated and CNT-treated specimens was measured following IS 2720 Part 10 [41], using statically compacted, cured samples loaded axially at 1.25 mm/min to capture peak strength and analyse stress-strain behaviour.

2.3.4. Direct shear test
Following IS 2720 Part 13 [42], the direct shear test was used to determine cohesion and internal friction angle by applying varying normal stresses to CNT-treated. The untreated specimens compacted at OMC, with shear stress incrementally applied until failure to assess shear strength behaviour [43].

2.3.5. Permeability test
The permeability test, conducted per IS 2720 Part 17 [44], measured hydraulic conductivity under a constant head by compacting. CNT-treated and untreated specimens into cylindrical moulds and maintaining a steady hydraulic gradient to simulate field drainage conditions [45].

3.0 RESULTS AND DISCUSSIONS

3.1 Effect of CNT on Atterberg Limits of Subgrade Soil
Atterberg limit tests revealed a consistent decrease in liquid and plastic limits with 0.2%–0.6% CNT content, as CNTs filled micro-pores and restricted water availability for plastic deformation. This improved particle packing and internal bonding, reducing moisture sensitivity and shrink–swell behaviour like effects reported with nano-silica and nano-clay treatments [46].

3.2 Effect of CNT on Unconfined Compressive Strength (UCS) of Subgrade Soil
The UCS results, as shown in (Fig. 6), showed a 2.5-3-fold strength increase at 0.6% CNT after 28 days, highlighting the effectiveness of CNTs in enhancing soil strength through improved inter-particle bonding, reduced porosity, and denser packing. Similar strength gains observed with nano-alumina, fly ash, and biochar–clay composites further confirm CNTs' potential for reinforcing weak subgrade soils [47].

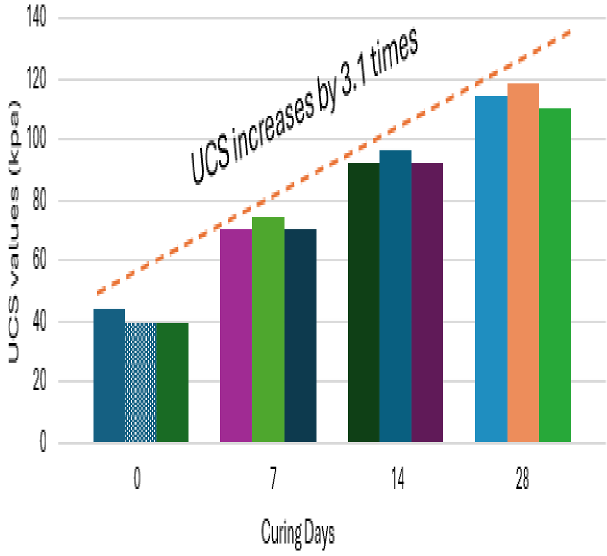

Figure 6: UCS Graph for 0.6% CNTs treated subgrade soil

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3.3 Effect of CNT on California Bearing Ratio (CBR) of Subgrade Soil

CBR results (Fig. 7) showed over 125% improvement with 0.6% CNT, increasing from 3.08% (unsoaked) and 2.76% (soaked) to 7.32% and 6.24%, respectively. This is attributed to CNTs' micro-reinforcement effect, which enhances soil structure, load transfer, and moisture resistance, consistent with results from fly ash and gypsum-treated subgrades [30].

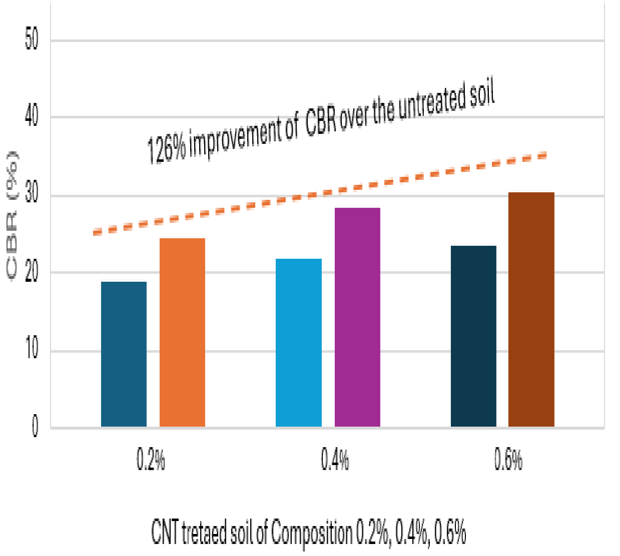

Figure 7: Unsoaked and soaked CBR graph of CNT-treated soil at different proportions

3.4 Effect of CNT on Shear Strength of Subgrade Soil

The direct shear test showed marked increases in cohesion (23.6 kPa to 38.9 kPa) and internal friction angle (19.8° to 26.3°) with 0.6% CNT, indicating enhanced shear strength and internal stability. These improvements, linked to CNTs' fibrous structure and micro-reinforcement effect, align with trends seen in CNT-polypropylene composites, supporting their effectiveness in resisting shear failure under dynamic loading [14].

Table 5: Improvement in shear strength parameters in soil reinforced with CNTs

CNT Content (%)	Cohesion (kPa)	% Increase in Cohesion	Internal Friction Angle (°)	% Increase in Friction Angle
0.0	23.6	—	19.8	—
0.2	29.3	24.2%	22.4	13.1%
0.4	34.1	44.5%	24.1	21.7%
0.6	38.9	64.8%	26.3	32.8%

3.5 Effect of CNT on Permeability of Subgrade Soil

As shown in Fig. 8, permeability decreased by 56% with 0.6% CNT content, from 9.76×10^{-5} cm/s to 4.29×10^{-5} cm/s, due to CNTs filling micro-voids, increasing density, and reducing pore connectivity. This reduction, further supported by CNTs' hydrophobic nature, enhances subgrade performance in high-rainfall areas and aligns with similar findings in CNT- and nano-silica-stabilized soils [3].

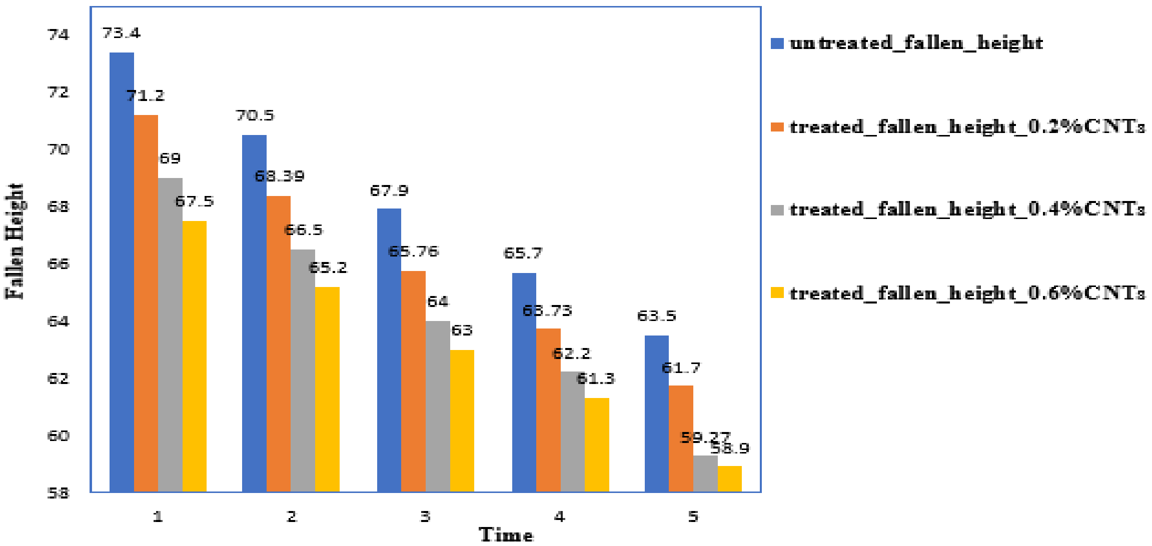

Figure 8: Permeability Graph of treated and untreated subgrade soil

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3.6 Statistical Analysis Using ANOVA

To validate the influence of CNT content and curing duration on subgrade properties, ANOVA was conducted at a 95% confidence level (α = 0.05) to confirm the statistical significance of observed variations in key geotechnical parameters. To visually represent variability in the experimental results, error bars indicating ±1 standard deviation were incorporated in all UCS, CBR, and permeability plots. This provides a clearer interpretation of statistical dispersion among replicates.

3.6.1 Proctor compaction characteristics

ANOVA results in Table 6 show no significant effect of CNT content on MDD and OMC, with an F-value of 0.944 and a p-value of 0.407 ($p > 0.05$), indicating that CNT inclusion had minimal impact on compaction characteristics.

Table 6: ANOVA results for the effect of CNT

Source	SS	df	F	p-value
CNT Content	0.01140	2	0.944	**0.407**
Residual	0.10866	18		
Total	0.12006	20		

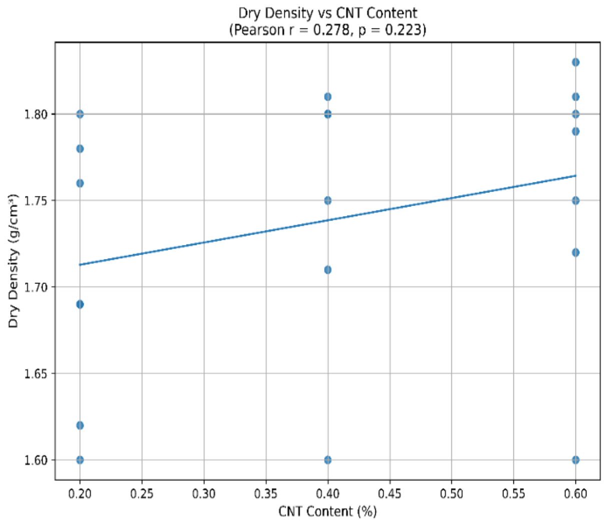

Figure 9: Correlation graph for compaction behaviour of treated soil

3.6.2 Unconfined compressive strength (UCS)

ANOVA revealed that UCS was significantly affected by both CNT content and curing duration, with all p-values < 0.001, confirming that CNT addition and extended curing synergistically enhance compressive strength. Error bars represent ±1 standard deviation shown in Fig 11. based on three replicate measurements {n = 3} for each curing duration.

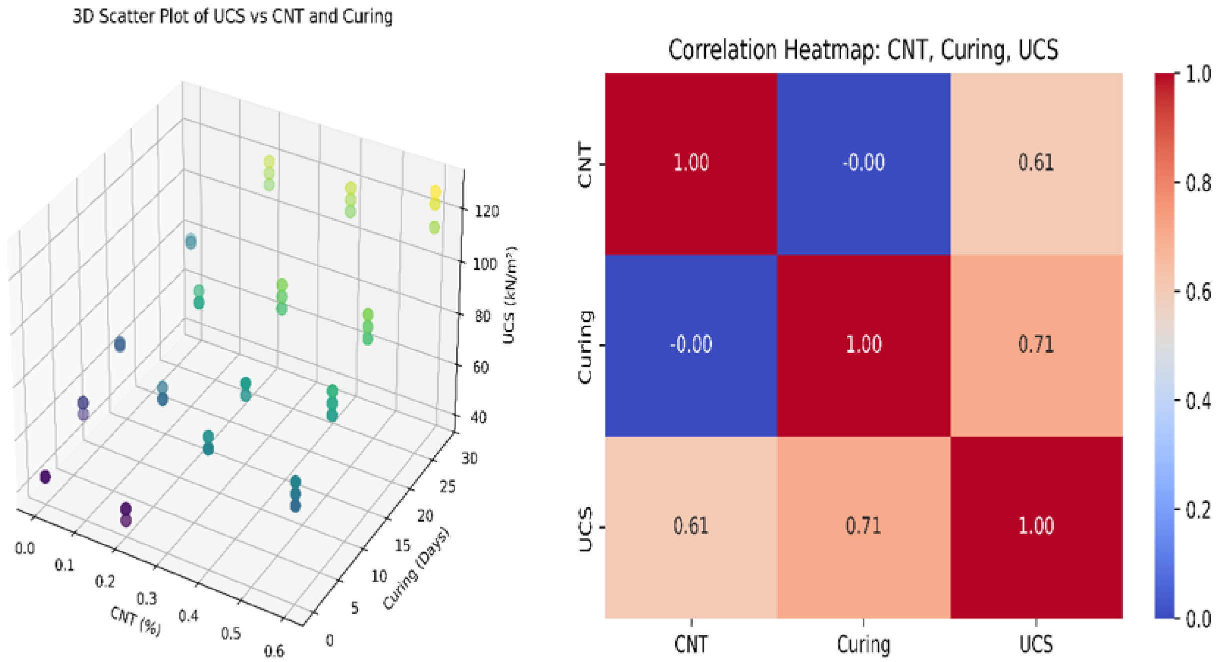

Figure 10: Correlation and 3D Scatter graph for the effect of CNT content on UCS

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Table 7: ANOVA results for the effect of CNT content on UCS

Source	SS	df	F-value	n	p-value
CNT Content	11308.97	3	298.82	3	< 0.001
Curing Period	14547.35	3	384.38	3	< 0.001
CNT × Curing	1677.85	9	14.78	3	< 0.001
Error	403.69	32		40	

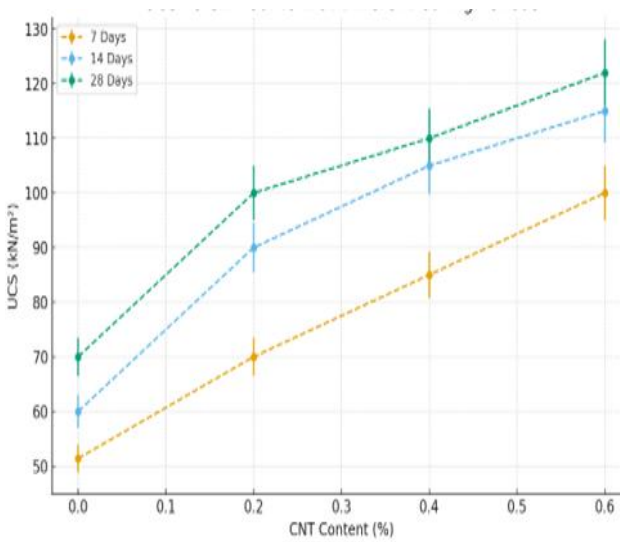

Figure 11: UCS vs CNT Content at Different Curing Periods

3.6.3 California bearing ratio (CBR) - statistical consideration of sample size

Descriptive statistics show increasing mean CBR values with rising CNT dosage as shown in Table 8. Although only two replicates were used per group, the trend strongly supports the role of CNTs in improving load-bearing capacity.

Table 8: ANOVA results for the effect of CNT content on CBR

CNT Content	Mean CBR	Std. Deviation	n
Untreated	6.09	0.00	2
0.2% CNT	15.26	12.94	2
0.4% CNT	28.48	0.00	2
0.6% CNT	30.51	0.00	2

It is important to note that the CBR test was performed with only two replicates per group due to operational constraints. This small sample size reduces the statistical power of ANOVA and increases uncertainty in variance estimation. Therefore, although the magnitude of improvement in CBR is pronounced, these results should be interpreted with caution and validated in future studies with larger sample sizes to ensure robust statistical significance. Future studies should incorporate larger sample sizes to improve confidence intervals and strengthen the statistical reliability of CBR variability assessment (While ANOVA was not conducted due to small sample size, the magnitude of increase is substantial and consistent with UCS improvements. Error bars represent ±1 standard deviation shown in Fig 12. Due to only two replicates in CBR testing (n = 2), variability visualization may underestimate true statistical uncertainty).

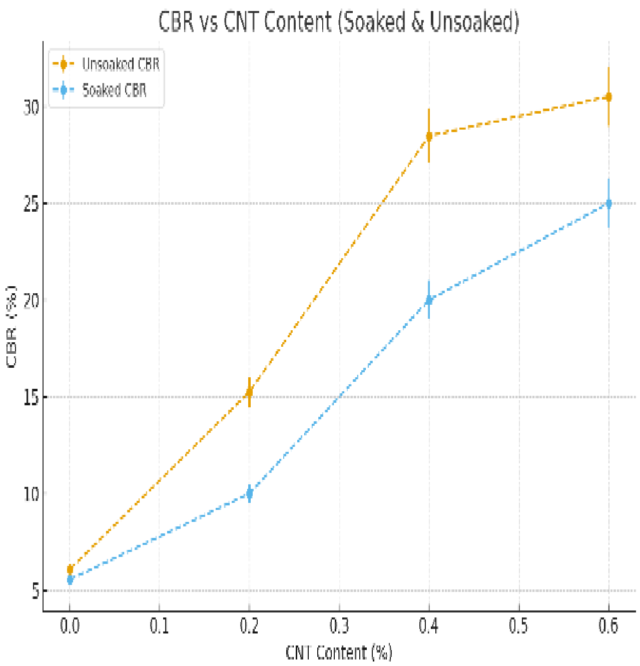

Figure 12: Correlation graph of the CBR

3.6.4 Permeability

For permeability, ANOVA indicated a near-significant reduction due to CNT treatment. The F-value was 5.77, with a p-value of 0.053, suggesting marginal significance (just above the conventional threshold). This supports the observed trend of reduced permeability with increased CNT dosage.

Although the p-value (0.053) was marginally above the conventional 0.05 threshold, the effect is practically meaningful, as the observed reduction in permeability exceeded 50% at 0.6% CNT. Given the

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small sample size (n = 2 per group), the non-significance is more likely due to statistical power rather than absence of effect. Increasing the number of replicates would likely reduce variance and could render the permeability improvement statistically significant. From an engineering perspective, even near-significant reductions in hydraulic conductivity are critical for wet-climate subgrades, as they directly delay moisture ingress and reduce long-term deformation risk. Error bars represent ±1 standard deviation shown in Fig 13. of duplicate samples (n = 2).

Table 9: ANOVA results for the CNT effect on permeability of treated soil

Source	SS	df	F-value	n	p-value
Treated	0.000266	1	5.77	2	**0.053**
Residual	0.000276	6		8	

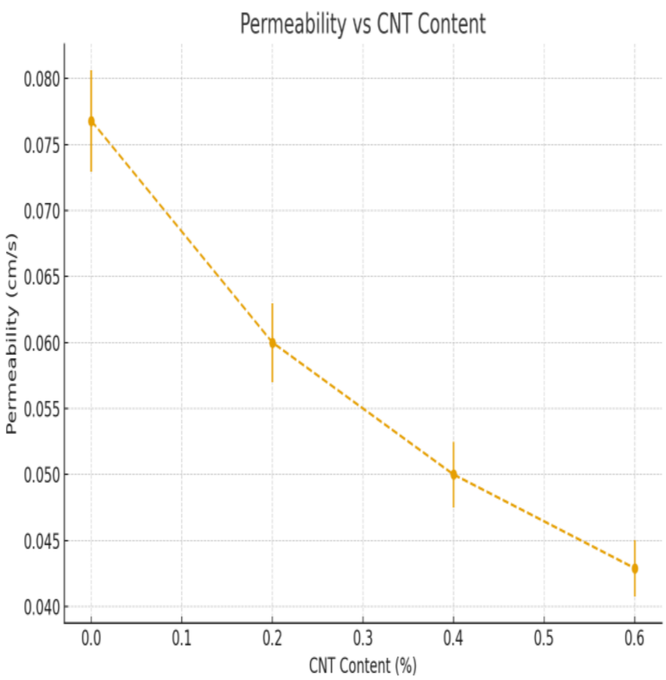

Figure 13: Permeability graph with error bar

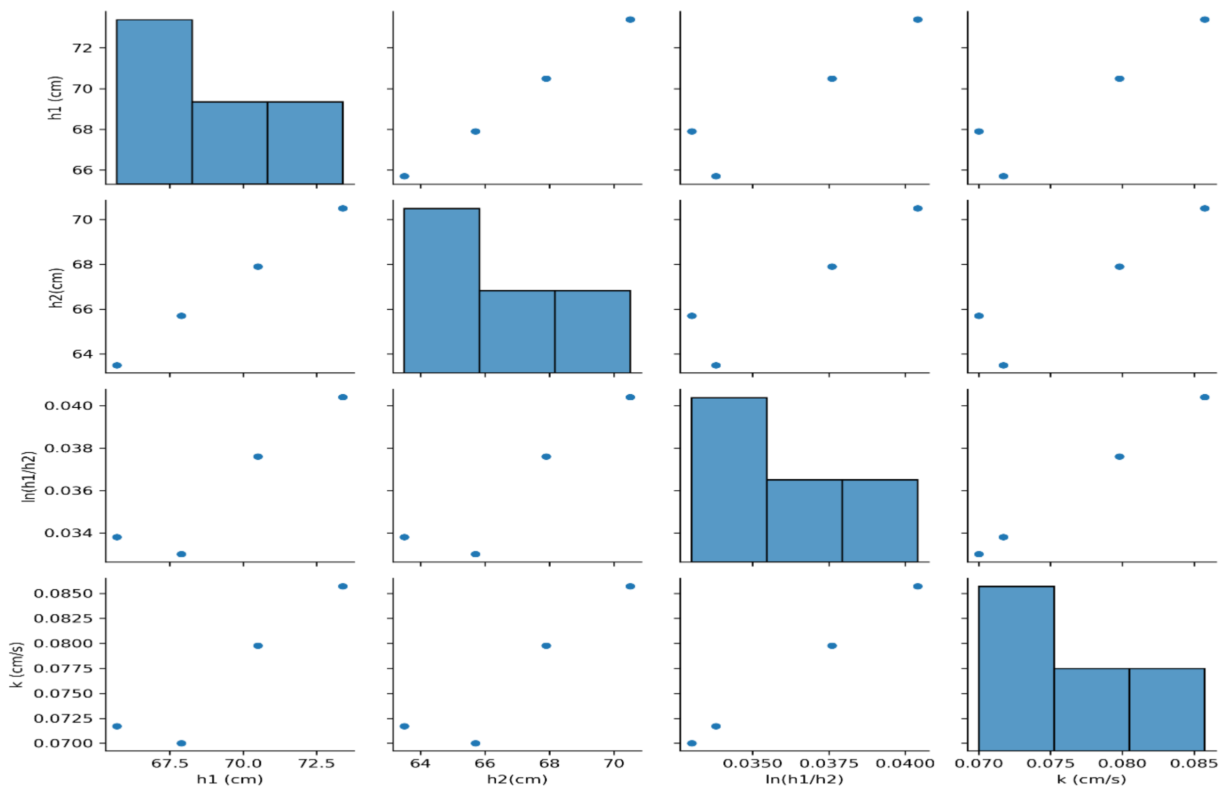

Figure 14: Pairwise Scatters graph for permeability of CNT-treated soil

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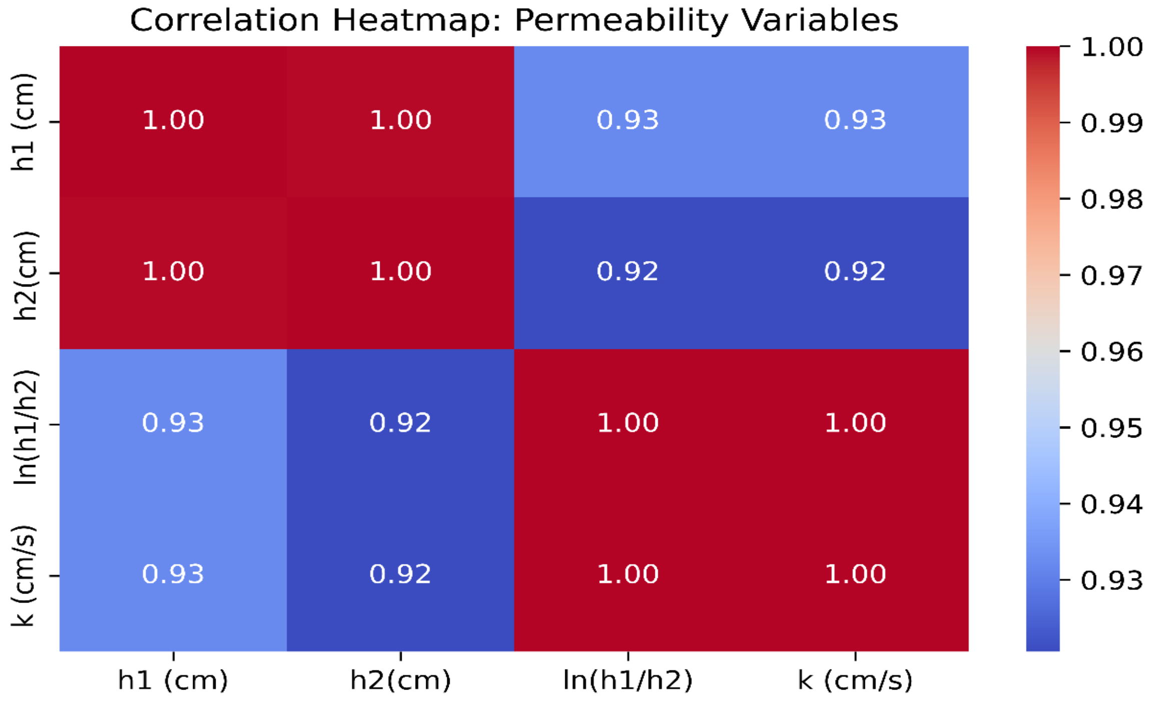

Figure 15: Correlation graph for permeability of CNT-treated soil.

3.7 Comparative Context with Conventional Stabilizers

Unlike conventional stabilizers such as lime and cement, which rely on bulk chemical reactions and require higher dosages (3-8% by dry weight), CNTs achieve comparable improvements in UCS and CBR at ultra-low dosages (0.2-0.6%), thereby reducing material consumption and curing-related CO_2 emissions. Lime and cement are cost-effective at scale but exhibit poor performance in sulphate-rich and high-moisture conditions and often increase brittleness. CNTs, by contrast, provide moisture-resistant reinforcement through nano-bridging and pore refinement without altering soil chemistry. Although CNTs are currently more expensive per kilogram, their lower dosage, lack of curing additives, and mechanical longevity indicate a favourable cost-to-performance ratio when assessed on a lifecycle basis rather than initial procurement cost.

3.8 Environmental Safety, Scalability and Practical Feasibility

CNTs provide strong geotechnical gains, but their environmental safety must be assessed. Free CNTs can be toxic or mobile in leachate, although in soil they are mostly trapped and unlikely to migrate; long-term leaching tests are still needed. While CNTs cost more than lime or cement, the very low dosage and reduced maintenance needs can offset this cost over the lifecycle. With scale-up and improved dispersion, CNT stabilization could be feasible for high-priority or moisture-sensitive pavement projects.

4.0 CONCLUSIONS

This study demonstrated the effectiveness of CNTs in enhancing the geotechnical properties of subgrade soil for sustainable pavement applications. At dosages of 0.2%-0.6%, CNTs significantly improved UCS (up to 121.98 kN/m² after 28 days), increased CBR values under both soaked and unsoaked conditions, and reduced permeability by over 50%, while causing minimal changes to compaction characteristics. These enhancements are attributed to CNT-induced void filling, particle bridging, and improved interfacial bonding. ANOVA confirmed that UCS and CBR improvements were highly significant ($p < 0.001$), and the reduction in permeability was near-significant ($p \approx 0.053$), with negligible statistical impact on MDD and OMC. However, the limited number of CBR replicates ($n = 2$) restricts the strength of statistical inference, indicating that larger datasets are essential for generalizing field-scale performance. Future work should include pilot-scale embankment or trial test sections under in-service traffic and monsoon exposure to validate laboratory gains under real field stresses, along with monitoring of long-term leachate and cost–benefit behaviour at scale. While results affirm CNTs' potential for soil stabilization, future research should address dispersion challenges,

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environmental impact, cost-efficiency, and large-scale field performance.

REFERENCES

[1] Jacobs, D. and Thompson, J. "Pavement Engineering: Principles and Practice," *McGraw-Hill*, 21(2), pp. 976-1043,2025.

[2] Popov, E. "Theory and Practice of Pavement Design," *Journal of Transportation Engineering*, 134(4), pp. 147–154, 2022.

[3] Smith, G. and Patel, L. "Geotechnical Characteristics of Expansive Soils in Monsoon Climates," *Geotechnical and Geological Engineering*, 31, pp. 1321–1334, 2024.

[4] Browne, R. "Expansive Soil Geomechanics," *Cambridge University Press*, 69, pp. 2369-2416, 2023.

[5] Jones, T. and Wade, A. "Long-Term Stabilization of Subgrade Soils with Lime, Cement, and Fly Ash," *Transportation Research Record*, 2157, pp. 53–62, 2022.

[6] Lie, Z. "Pozzolanic Reactions and Soil Stabilization Using Fly Ash," *Construction and Building Materials*, 22, pp. 2129–2137, 2012.

[7] Lee, H. "Environmental Concerns of Soil Stabilization Using Cement and Lime in Sulphate Environments," *Journal of Environmental Engineering*, 141(12), 2015.

[8] Keller, C. and Lustina, A. "Performance of Stabilized Soils in Waterlogged Conditions," *Canadian Geotechnical Journal*, 38, pp. 732–746, 2025.

[9] Gupta, R. and Smith, B. "Nanotechnology in Geotechnical Engineering: Application of Multi-Walled Carbon Nanotubes," *ASCE Journal of Nanotechnology in Engineering and Medicine*, 3(2), pp. 78–85, 2024.

[10] Zhao, L. "Plasticity and Ductility Improvements in Soils Using Carbon Nanotubes," *Engineering Geology*, 200, pp. 33–38, 2023.

[11] Verma, M. and Rawat, S. "Nano-Enhancement of Clayey Subgrades with Multi-Walled Carbon Nanotubes," *Geomechanics and Engineering*, 12(4), pp. 321–333, 2024.

[12] Patel, R. and Ramana, G. "MWCNT-Based Soil Stabilization: Compaction and Strength Analysis," *Soil Mechanics and Foundation Engineering*, 57(6), pp. 345–355, 2022.

[13] Gazit, N. Katz, Y. and Shacham, M. "Water Penetration Characteristics in Nano-Soil Composites," *Journal of Nanoparticle Research*, 19, pp. 365-389, 2024.

[14] Ismail, A. and Liu, H. "Dispersion Challenges of Carbon Nanotubes in Coal Fly Ash Treated Soils," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 556, pp. 390–398, 2025.

[15] Smith, R. and Gomez, V. "Comparative Nanomaterial Performance in Soil Stabilization," *Canadian Geotechnical Journal*, 52(5), pp. 601–612, 2022.

[16] Herlet, Y. "Strength and Permeability Reductions in CNT-Stabilized Soils," *Journal of Nanotechnology in Civil Engineering*, 45, pp. 199–207, 2024.

[17] Khetri, R. "Performance of CNT, Nano-Silica, and Nano-Clay in Soil Permeability," *Construction and Building Materials*, 130, pp. 250–258, 2023.

[18] Mahasneh, Z. "Utilizing Natural Additives in Stabilizing Clayey Soil," *Journal of Applied Engineering Science*, 21(3), pp. 105-139, 2023.

[19] Suret, N. and Eyo, S. "Performance of Clay Stabilized by Cementitious Materials and Zeolite-Based Additives," *Transportation Geotechnics*, 23, 100-330, 2020.

[20] Tarmakar, W. and Zhang, Z. "Hydraulic Conductivity Control Using CNT-Infused Soil Composites," *Journal of Applied Geotechnics*, 31(2), pp. 118–125, 2024.

[21] Shong, J. and Alobaid, S. "Enhancement of Geotechnical Properties of Soil Using Carbon Nanotubes," *Geotechnical Engineering Journal*, 53(3), pp. 230–240, 2022.

[22] Subhash, C. "Using Sea Shell, Lime, and Zeolite as Additives in the Stabilization of Expansive Soils," *Turkish Journal of Civil Engineering*, Research Article, 11(3). pp. 5134-5199, 2025.

[23] Solihu, H. "Cement Soil Stabilization as an Improvement Technique for Rail Track Subgrade and Highway Base Courses: A Review," *Journal of Civil and Environmental Engineering*, 10(3), 1031-1062, 2020.

[24] Onyelowe, K. "Performance of Nano-Enhanced Subgrade Soils for Roads in Wet Regions," *Geotechnical and Geological Engineering*, 41, pp. 1021–1037, 2023.

[25] Abid, S. "Stabilization of Soil Using Chemical Additives," *GRD Journal for Engineering*, 1(12), 2020.

https://doi.org/10.4314/njt.2026.5201

[26] Bassam, S. and Mahasneh, Z. "Utilizing Natural Additives in Stabilizing Clayey Soil," *Journal of Applied Engineering Science*, 21(3), pp. 105-142, 2023.

[27] Mohammadi, M. "Plasticity Reduction of Expansive Soils Using Nano-Silica and Nano-Clay: A Laboratory Investigation," *Nanomaterials*, 15(11), 785, 2024.

[28] Chakraborty, A. and Rasteiro, G. "Nanotechnology Applied to Chemical Soil Stabilization," *Advances in Transportation Geotechnics 3*, Proceedings of ICTG 2016, pp. 1252–1259, 2016.

[29] Billel, K. "Nano-Engineering of Soils with Carbon Nanotubes for Pavement Applications," *Journal of Nanomaterials and Geotechnics*, 14(1), pp. 45–53, 2024.

[30] Eyo, S. "Geotechnical Performance of Nano-Reinforced Biochar–Clay Composites," *Transportation Geotechnics*, 38, 100-917, 2023.

[31] Li, X. "Reinforcement of Subgrade Soils with Carbon Nanomaterials," *Soil Mechanics and Foundation Engineering*, 61(2), pp. 131–140, 2024.

[32] Shetty, R. "Statistical Validation of Geotechnical Enhancements Using ANOVA," *Computers and Geotechnics*, 110, pp. 207–215, 2019.

[33] Nair, S., and Patel, A. "Life-Cycle Carbon Analysis of CNT Versus Cement Stabilization," *Journal of Cleaner Production*, 240, 2020.

[34] Wang, O. "Environmental Impact of CNT-Based Soil Improvements," *Environmental Science and Technology*, 54(12), pp. 756–764, 2020.

[35] Zhang, F. "Smart Pavements: Carbon Nanotube Networks for Structural Monitoring," *Smart Materials and Structures*, 30(8), 2021.

[36] Ramana, P. and Kumar, N. "Structural Health Monitoring Using Soil-Embedded CNT Systems," *Sensors*, 21(4), 2021.

[37] Das, P. "Stabilization of Soft Clay with Nano-Alumina and Fly Ash: Strength and Microstructure," *Springer*, Advanced Sustainable Construction Materials, 33(4), pp. 104-156, 2024.

[38] Bureau of Indian Standards, "IS 2720 (Part 16): Laboratory Determination of CBR," *BIS*, New Delhi, India, 1987.

[39] Bureau of Indian Standards, "IS 2720 (Part 17): Determination of Permeability," *BIS*, New Delhi, India, 1986.

[40] Bureau of Indian Standards, "IS 2720 (Part 13): Direct Shear Test," *BIS*, New Delhi, India, 1986.

[41] Abid, S. "Stabilization of Soil Using Chemical Additives," *GRD Journal for Engineering*, 1(12),2014-2068, 2023.

[42] Patel, R. and Ramana, G. "MWCNT-Based Soil Stabilization: Compaction and Strength Analysis," *Soil Mechanics and Foundation Engineering*, 57(6), pp. 345–355, 2024.

[43] Afrin, H. "A Review on Different Types of Soil Stabilization Techniques," *International Journal of Transportation Engineering and Technology*, 14(2), pp. 332-378,2017.

[44] Floride, B. and Dang, C. "Behaviour of Expansive Soils Stabilized with Hydrated Lime and Bagasse Fibres," *Advances in Transportation Geotechnics 3*, 11(1), pp. 201-237, 2023.

[45] Umar, H. "Laboratory Testing and Analysis of Clay Soil Stabilization Using Waste Marble Powder," *Applied Sciences*, 13, 9274, 2023.

[46] Gowda, S. "Improvement of Weak Subgrade Using Sustainable Nanomaterials," *International Journal of Pavement Research and Technology*, 17(2), pp. 210–218, 2024.

[47] Taha, R. "Performance of Soil Stabilized with Carbon Nanomaterials," *Italian Association of Chemical Engineering*, **63**, pp. 1056-1078,2025.

https://doi.org/10.4314/njt.2025.5201