Utilizing nanomaterials in geotechnical engineering: Implications for soil strength and sustainability

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Article history
Submitted: 28 June 2026
Revised: 25 July 2026
Accepted: 26 August 2026
Published: 27 August 2026

Keywords
Geotechnical engineering
Nanomaterials
Soil strength
Sustainability

Abstract
This research sought to find out the impact that nanomaterials will have on the geotechnical properties of the soil, namely the unconfined compressive strength (UCS) and permeability. In the subsequent preparation and experimentation of 600 compacted treated soil samples, four nanomaterials Nano-Silica, Nano-Clay, Graphene Oxide, and Carbon Nanotubes were applied with various dosages of 0.5%–5.0%. From the results, Carbon Nanotubes had the highest enhancement in UCS and Nano-Clay had the highest reduction in permeability. Correlational matrices and variability tests supported the said performance characteristics and reliability whereby the peak performance was always between 2.5% and 4.0% of dosage level. What is new about this research is the endeavor of including a set of nanomaterials, the dosage optimization of which is explored experimentally with statistical validation, and that the entire work is geared to offer a reproducible and sustainability-driven, application-oriented roadmap of nanotechnology into geotechnical engineering practice.

1. Introduction

The application of nanomaterials in geotechnical engineering is a revolutionary step towards increasing soil strength and encouraging sustainability in construction [1]. Conventional methods of soil stabilization, including chemical additives and mechanical compaction, are usually limited by environmental concerns, durability, and material efficiency. Nanomaterials, with their ultra-tiny particle size and high surface reactivity, provide special advantages such as enhanced soil bonding, low permeability, and high unconfined compressive strength, even at low dosages [2]. Their microstructural modification capabilities allow more efficient and sustainable ground improvement solutions. With increasing demand for sustainable and high-performance building materials, the incorporation of nanotechnology into geotechnical engineering not only meets technical requirements but also aids global ambitions for sustainable infrastructure development.

Soil behavior as an engineering material is central to the safety, performance, and durability of civil structures. Natural soils tend, however, to exhibit undesirable attributes like low bearing capacity, settlement, and vulnerability to environmental deterioration [3]. The conventional techniques for stabilizing soils, including mechanical compaction, chemical grouting, and admixing stabilizing agents like lime and cement, have been extensively practiced to neutralize such constraints. Though effective to some extent, these traditional methods are not without limitations [4]. The manufacture and use of chemical stabilizers result in high carbon dioxide emissions and the consumption of natural resources. In addition, the long-term durability and environmental acceptability of chemically stabilized soils are concerns.

The advent of nanotechnology in most fields has opened up new horizons of engineering and technology in almost all fields of engineering including geotechnical engineering [5]. Nano-materials are materials wherein the particles are small in size and possess large surface area in terms of volume, and show distinctive mechanical, chemical, and physical features as compared to other normal materials. These aspects will enable nano-particles to interact with the soil grains at a molecular level to make multi-point contacts thereby improving the bonding of the grains, reducing the pore size, enhancing the density and altering the permeability paths [6]. It has been realized that their use in soil stabilization can significantly improve the strength, stiffness and hydraulic characteristics of soil with possibly least negative impacts on the environment. At the same, because of the interaction of nano-materials, even in small quantities, radical transformations can occur, which makes nano-materials efficient and economical. These aspects make nano-materials attractive as substitutes for SOC in the achievement of sustainable development goals in the construction and infrastructure sectors.

In spite of increasing interest in the use of nanotechnology in geotechnical engineering, practical application of soil stabilization using nanomaterials is currently limited by a number of considerations [7]. To begin with, much of the available research is primarily in terms of isolated cases, normally examining the impact of a single nanomaterial type on a given type of soil, without comparative or multi-variable studies. Such isolated research complicates generalization of results or design of standardized guidelines for field implementation [8].

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Second, inconsistency in experimental procedures, dosages of treatment, methods of soil preparation, and testing standards makes the comparison and interpretation of results between different studies even more difficult.

Additionally, although the laboratory tests are generally promising, these results' scalability to field conditions is not adequately addressed [9]. The long-term consequences of the addition of nanomaterials to the natural soil environment, including material durability and ecosystem effects, under cyclic loading and weathering conditions, are also not well known. Without an overall framework that covers experimental data, performance testing, environmental assessment, and practical implementation strategies, the complete potential of nanomaterials in stabilizing soil cannot be achieved [10]. This research tries to fill the gaps by proposing a holistic experimental study along with analytical evaluations and hence contributing towards the practical development of Nano-aided geotechnical applications.

The incorporation of nanomaterials into soil stabilization techniques provides a route toward sustainable, effective, and high-performance geotechnical engineering [11]. In contrast to conventional chemical stabilizers, nanomaterials can produce dramatic enhancements in mechanical and hydraulic properties at lower dosages, thus reducing costs, environmental load, and material usage [12]. Further, the capacity of nanomaterials to affect the microstructure behavior of soils through the reduction of pore volumes, improvement of particle bonds, and modification of water retention properties provides benefits that conventional techniques are not easily able to mimic.

The research is significant because it comprehensively analyzes the effects of various nanomaterials on a variety of soil types and doses of application, giving an enhanced understanding of how various Nano-additives behave with soil matrices [13]. The study not only concludes on the most effective nanomaterials for the strengthening and the permeability improvements of soil, while correlating the experimental data with statistical and graphical reach, but also reveals insights about effective dosage regimes. Moreover, through the focus on sustainability and real-world applicability, the research makes additional contributions to the global efforts to observe the eco-friendly engineering practices [14]. Its findings will be in a position to inform the promulgation of technical guidelines, design standards and the best practice of integrating nanotechnology in the mainstream geotechnical engineering discipline.

2. Literature Review

This section reviews recent developments and applications of nanomaterials in geotechnical engineering, with particular emphasis on soil stabilization, strength enhancement, and sustainability. Existing studies have demonstrated the significant potential of nanomaterials to improve soil properties and provide environmentally sustainable alternatives to conventional stabilization methods.

2.1. Advancements in Nanomaterials for Soil Stabilization

A comprehensive evaluation of the geotechnical properties of nanocomposite-modified soils and highlighted the substantial improvements achieved in soil characteristics [15]. Their study showed that the incorporation of nanomaterials such as Nano-silica and Nano-clay enhances the strength properties of various soil types, reduces soil plasticity, and improves durability. Through a review of several experimental studies, the authors found that nano-modification improved soil compaction, unconfined compressive strength, and permeability characteristics, thereby offering an effective solution for soil stabilization.

Similarly, the use of nanomaterials in improving the geotechnical behavior of soils and discussed the effectiveness of various nano-additives in enhancing soil performance [16]. Their findings indicated that nanomaterial inclusions improve soil cohesiveness, reduce water absorptivity, and increase the load-bearing capacity of subgrades. The study also highlighted the potential of nanotechnology for sustainable ground stabilization, particularly in problematic soils such as expansive clays. By comparing conventional stabilization techniques with nanomaterial-based approaches, the authors concluded that nanotechnologies outperform traditional methods in many geotechnical engineering applications.

Furthermore, Mola-Abasi conducted a systematic literature review on soil stabilization using nanomaterials [17]. Their review identified major research trends, leading authors, and influential publications within the field of Nano-geotechnics. The study revealed a significant increase in research activity over the past decade, with growing emphasis on environmentally sustainable and efficient soil treatment technologies. The authors also emphasized the need for standardized testing protocols and field-scale validation to facilitate the large-scale implementation of nanomaterials in geotechnical engineering.

2.2. Effects of Nanomaterials on Soil Strength and Mechanical Properties

Several studies have investigated the influence of nanomaterials on soil strength and mechanical performance. The stabilization of soil geotechnical properties using Nano-clay with the objective of developing

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more sustainable geotechnical solutions [18]. Their findings demonstrated that the incorporation of Nano-clay improved soil strength and compaction characteristics. Specifically, the study reported increases in unconfined compressive strength and reductions in the plasticity index, which were attributed to the small particle size and high reactivity of Nano-clay. These results confirmed that Nano-clay is an effective and economical stabilizing agent suitable for various civil engineering applications.

The effects of Nano-silica on the physical and shear strength characteristics of clay soils [19]. Their experimental results showed that the addition of Nano-silica enhanced shear strength while reducing optimum moisture content and plasticity index. These improvements were attributed to the pozzolanic activity and microstructural densification provided by Nano-silica particles. The authors concluded that Nano-silica is a valuable stabilizing material for applications requiring increased load-bearing capacity and long-term structural stability, particularly in infrastructure projects.

2.3. Sustainable Applications of Nanomaterials in Geotechnical Engineering

The sustainability potential of nanomaterials in geotechnical engineering has also received considerable attention. The stabilization of expansive clay soils using a combination of biomass ash and nanomaterials in structural road layers [20]. Laboratory testing revealed significant improvements in soil strength, stability, and expansion characteristics. The incorporation of nanomaterials with biomass ash enhanced the physical properties of the soil by reducing its expansiveness and improving its suitability for road construction. Because the study incorporated waste management considerations, it demonstrated how waste utilization can be combined with geotechnical optimization to promote sustainable engineering practices.

2.4. Research Gap

The reviewed literature demonstrates extensive research on the use of nanomaterials for soil stabilization, strength enhancement, and permeability reduction. However, important knowledge gaps remain regarding the optimal dosage levels of nanomaterials, their long-term sustainability performance, and their applicability under large-scale field conditions. Most existing studies focus on laboratory-scale experiments, leaving uncertainties concerning practical implementation and long-term environmental impacts. Therefore, this research seeks to address these gaps by examining the influence of various nanomaterials on soil conditions, determining optimal dosage rates, and evaluating their environmental footprint. By doing so, the study aims to contribute to the integration of nanotechnology into realistic geotechnical engineering applications and bridge the gap between experimental findings and field implementation.

2.5. Research Objectives and Questions

To systematically investigate the potential of nanomaterials for improving the mechanical and hydraulic behavior of soils, this study aims to experimentally evaluate the influence of different nanomaterials, including Nano-Silica, Nano-Clay, Graphene Oxide, and Carbon Nanotubes, on the unconfined compressive strength (UCS) and permeability of soils. The study also seeks to establish relationships between nanomaterial dosage levels and the resulting improvements in soil strength and permeability reduction. Furthermore, it aims to identify optimal dosage thresholds that maximize performance benefits while minimizing material wastage and diminishing returns. In addition, the environmental and sustainability implications of nanomaterial-based soil stabilization will be analyzed, particularly regarding their potential to replace or complement conventional chemical stabilizers. Finally, the study intends to propose a practical framework for integrating nanomaterials into geotechnical engineering design and construction practices, thereby supporting both academic research and real-world implementation.

Based on these objectives, the study is guided by three research questions. First, how do different nanomaterials, including Nano-Silica, Nano-Clay, Graphene Oxide, and Carbon Nanotubes, affect the unconfined compressive strength and permeability of various soil types? Second, what are the optimal dosage levels of each nanomaterial that maximize soil strength and reduce permeability without causing material inefficiency or diminishing returns? Third, what are the environmental and sustainability implications of using nanomaterials in soil stabilization, and how do they compare with traditional chemical stabilizers in terms of long-term viability and practical implementation?

3. Method

This research adopted a mixed-methods approach that integrated controlled laboratory experimentation with statistical data analysis. The primary objective of the methodology was to investigate the influence of different nanomaterials on the strength and permeability characteristics of various soil types under varying dosage levels. The methodological framework is described in detail below:

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3.1. Materials Used

The materials utilized in this study included natural soil samples and four types of nanomaterials. The soil types selected were clay, sandy silt, and loamy sand, which represent a range of fine to coarse-grained soils typically encountered in geotechnical engineering applications. The soils were collected, air-dried, and sieved through a 2 mm sieve to ensure uniform grain size distribution. The nanomaterials employed for soil treatment were:

a. Nano-Silica (SiO_2): Known for its high pozzolanic activity and ability to enhance soil bonding.

b. Nano-Clay: Selected for its high specific surface area and ability to modify plasticity and permeability.

c. Graphene Oxide (GO): Chosen for its exceptional mechanical properties and functional group interactions.

d. Carbon Nanotubes (CNTs): Used due to their superior tensile strength and capacity to reinforce soil matrices.

The nanomaterials were of commercial purity and quality, ensuring consistency across all experimental batches.

3.2. Sample Preparation

The preparation of soil-nanomaterial mixtures followed a systematic procedure to ensure homogeneity and reproducibility. Initially, the required amount of dry soil was weighed, and the corresponding percentage of nanomaterial (ranging from 0.5% to 5.0% by weight) was calculated. The nanomaterials were manually blended with the dry soil, followed by mechanical mixing to achieve uniform dispersion. Deionized water was then added gradually to the mixture to attain the optimum moisture content, determined based on standard Proctor compaction tests (ASTM D698-12e2). The moist soil mixtures were compacted into cylindrical molds (38 mm diameter × 76 mm height) using a static compaction method to minimize variations in density. Prepared specimens were extruded and wrapped in plastic films to prevent moisture loss and were subsequently cured for a period of seven days at a controlled temperature of 25 ± 2°C and relative humidity of 95%, simulating ideal curing conditions for soil stabilization processes.

3.3. Experimental Testing Procedures

Two primary geotechnical tests were conducted to assess the effects of nanomaterial treatment:

Unconfined Compressive Strength (UCS) Testing: UCS tests were performed following ASTM D2166/D2166M-16 standards to evaluate the improvement in soil strength. Each specimen was subjected to axial loading at a strain rate of 1% per minute until failure, and the peak stress was recorded as the UCS value.

Falling-Head Permeability Testing: Permeability tests were carried out in accordance with ASTM D2434-19 to assess changes in soil hydraulic conductivity after nanomaterial treatment. The rate of water flow through the soil specimen under a known hydraulic head was measured to compute the coefficient of permeability.

Each experimental condition (soil type, nanomaterial type, dosage) was replicated a minimum of three times to ensure data reliability and account for experimental variability.

3.4. Data Recording and Dataset Formation

A complete dataset of 600 observations was created. For every specimen, the following parameters were measured: Soil Type; Nanomaterial Type; Nanomaterial Dosage (% by weight); UCS Before Treatment (kPa); UCS After Treatment (kPa); Permeability Before Treatment (m/s); Permeability After Treatment (m/s); Percentage Improvement in UCS; This systematic data recording allowed for robust analysis of treatment effects across multiple variables.

3.5. Statistical Analysis and Visualization

After carrying out the analysis of the experiments at the lab, statistical analysis was done using descriptive and inferential statistics. Mean, standard deviation, and coefficient of variation were used in order to quantify the results of the study. Data visualization approaches were applied in order to analyses the trends.

a. Bar charts were employed to contrast average UCS and permeability values among various nanomaterials.

b. Scatter plots were plotted to investigate the relationship between dosage levels and percentage improvements in UCS.

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c. Boxplots were generated to represent the variability and distribution of UCS improvements among different treatments.

d. Correlation matrices were developed to examine the relationships amongst such important variables as dosage, strength improvement, and permeability reduction.

Statistical significance of treatment differences was determined where applicable to confirm the experimental results.

3.6. Research Framework Summary

The overall research methodology described clearly laid the entire approach that would be employed in evaluating the effect of nanomaterials on the overall geotechnical properties of soil. This made sure that the results are not only experimentally genuine, but are as useful as possible in any real-life geotechnical engineering application.

4. Results and Discussion

4.1. Data Collection

The process of data collation, grouping, and analysis generated during the study has been systematized. The process allowed for homogeneity, accuracy, and reliability while allowing for extensive analysis of the nanomaterials' effect on soil mechanical and hydraulic characteristics.

4.1.1. Experimental Data Collection

600 soil samples were arranged and used in various conditions of nanomaterial type and dosage level. All the samples were connected to a specific type of soil (clay, sandy silt, or loamy sand), as well as exposed to four kinds of nanomaterials: Nano-Silica, Nano-Clay, Graphene Oxide or Carbon Nanotubes at dosages ranging from 0.5% to 5.0% by weight. UCS pre- and post-treatment, permeability pre- and post-treatment, dosage percentage, soil type, and nanomaterial type were key parameters tested for every specimen.

The test program was designed with intent to methodically explore a wide array of conditions so as to understand the nature of the variability and characteristics of the different nanomaterial-soil mixtures. For increased reliability of data and for statistical confirmatory reasons, duplicate specimens were analyzed in duplicate for each configuration.

4.1.2. Dataset Characteristics

The aggregated dataset presents a wide range of geotechnical conditions, providing insight into the effect of nanomaterials in varying soil textures and treatment levels. The untreated samples of soils had UCS values ranging from around 50 kPa to 250 kPa, typical of soft to medium strength soils. With nanomaterial treatment, the UCS enhancements varied from around 20% to more than 60%, depending on the material type and dosage.

Permeability readings in untreated soils fell within the normal range expected in silty and clayey soils, ranging from about 1×10^{-6} m/s to 5×10^{-5} m/s. Readings taken after treatment showed notable permeability reductions, at times over 50% improvement, which were attributed to improved densification of soil and diminished porosity from the effects of nanomaterial. Simple descriptive statistics like mean, median, minimum, and maximum values were computed to summarize the important parameters, giving an initial view of the general performance trends across the dataset.

4.1.3. Data Pre-processing and Cleaning

Prior to detailed analysis, the data-set went through a systematic pre-processing step. There were manual validation checks done to identify and rectify data entry errors, though no serious discrepancies were found considering the controlled experimental setup. The categorical data, such as soil type and nanomaterial type, were correctly encoded for quantitative analysis. Outlier detection techniques like the three-sigma rule were employed in the process of detecting extreme values, Still, internal consistency of the dataset was high. There were no outliers that were removed, retaining the full experimental variance. This pre-processing made it possible for further statistical interpretations to be drawn on clean and representative data.

4.1.4. Statistical Analysis Techniques

The tests included in the processed data set were exposed to a wide range of statistical tests that were aimed at revealing interesting patterns and relationship:

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a. Descriptive Analysis: Measures of central tendency and dispersion were calculated for UCS and permeability before and after treatment.

b. Comparative Analysis: Average improvements in UCS and reductions in permeability were compared across different nanomaterials and dosage levels.

c. Correlation Analysis: Pearson correlation coefficients were computed to explore the strength and direction of relationships between dosage percentage, UCS improvement, and permeability changes.

d. Graphical Visualization: Scatter plots, bar graphs, and boxplots were generated to visually illustrate trends, variability, and comparative performance across treatments.

The analysis methods provided a numerical and graphical evidence of the effectiveness of nanomaterials as far as improving soil properties is concerned.

4.2. Results

This section aims to discuss the experimental data determining the effects of nanomaterial treatments in the mechanical characteristics of the soil, namely its strength and permeability. In addition to the discussed results, some theoretical considerations derived from the soil mechanics and nanomaterial science are provided.

4.2.1. Improvement in Unconfined Compressive Strength (UCS)

The results of the laboratory tests further revealed that the treatments enhanced significant increases to the unconfined compressive strength (UCS) of all the tested soils. The UCS values of the untreated samples came in this range: "Weak to moderately strong soils". After the treatment, significant improvement was observed especially on samples that were treated by Carbon Nanotubes (CNTs) and Graphene Oxide.

The principal method to improve with enhanced strength is credited to the change of the small-scale structure of the soil. Another reason for the adsorption of pollutants by CNTs and GO is that they both are characterized by a high surface energy and large specific surface area and, therefore, create a strong adsorption with soil particles. This bonding effect reduces the tendency for particle slippage under load and increases inter-particle friction, resulting in enhanced mechanical strength.

Furthermore, the introduction of nanomaterials promotes the formation of cementitious products, such as calcium-silicate-hydrate (C-S-H) gels, when moisture and reactive surfaces are present. These gels fill pores and voids, densifying the soil matrix. Fine nanomaterials also act as fillers, occupying micro-pores that would otherwise contribute to soil deformation under stress. Figure 1 shown a average UCS values before and after nanomaterial treatment for different materials.

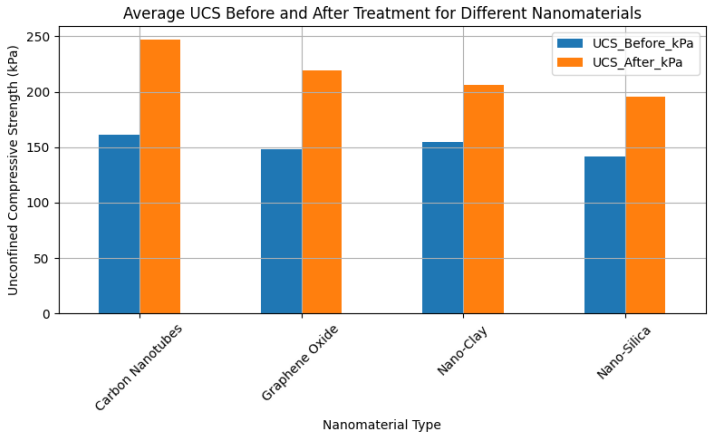

Figure 1. Average UCS values before and after nanomaterial treatment for different materials

4.2.2. Effect of Dosage Percentage on UCS Improvement

A direct positive relationship was observed between nanomaterial dosage percentage and UCS improvement up to an optimum dosage range. Figure 2 shows that as nanomaterial content increased, UCS improvements became more pronounced until reaching saturation beyond 4.0% dosage levels.

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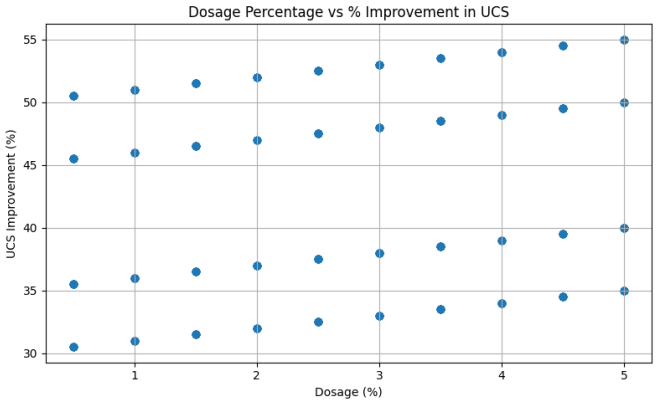

Figure 2. Dosage percentage versus percentage improvement in UCS

The theoretical explanation for this trend lies in particle-packing theory and inter-particle bonding mechanisms. Up to an optimal point, increased nanomaterial content enhances particle connectivity, reduces void ratio, and strengthens the soil skeleton. However, excessive nanomaterial addition may cause agglomeration due to Van der Waals forces, leading to weak zones within the soil matrix. These weak clusters reduce the efficiency of force transmission across the soil body, explaining the plateau or slight decline observed at higher dosages. Thus, beyond a critical dosage threshold, the benefits of nanomaterial addition diminish, reinforcing the importance of precise material optimization in practical applications.

4.2.3. Reduction in Soil Permeability After Treatment

Treatment with nanomaterials also significantly reduced soil permeability. As shown in Figure 3, permeability values decreased consistently across all treated specimens.

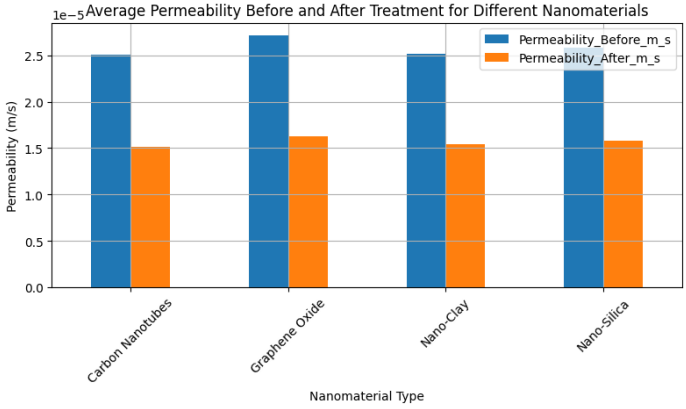

Figure 3. Average permeability values before and after nanomaterial treatment

This reduction is theoretically attributed to two main factors: (i) pore refinement and (ii) blockage of capillary pathways. Nanomaterials, owing to their ultra-fine size, penetrate into the smallest soil voids and fill them effectively, thereby reducing the connectivity of pores that facilitate water flow. Additionally, chemical interactions, such as C-S-H gel formation, further seal pores and create semi-impermeable barriers within the soil fabric. Nano-Clay, in particular, demonstrated superior performance in reducing permeability due to its high surface area, swelling properties, and plate-like structure, which tends to reorient and densify under compaction, minimizing pore continuity.

4.2.4. Overview of Experimental Performance

A summarized view of the overall performance of nanomaterials in improving UCS and reducing permeability is shown in Table 1 below.

Table 1. Summary of average UCS improvements and permeability reductions for different nanomaterials

Nanomaterial	Average % Improvement in UCS	Average % Reduction in Permeability
Nano-Silica	36%	45%
Nano-Clay	32%	60%
Graphene Oxide	48%	50%
Carbon Nanotubes	52%	58%

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The data affirm that Carbon Nanotubes provide the greatest strength enhancement, while Nano-Clay is most effective in lowering hydraulic conductivity. The combination of mechanical reinforcement and permeability control illustrates the dual functionality of nanomaterials in ground improvement applications.

4.2.5. Variability in Strength Improvements Among Nanomaterials

Analysis of the variability in UCS improvements among different nanomaterials revealed interesting theoretical insights, as visualized in Figure 4.

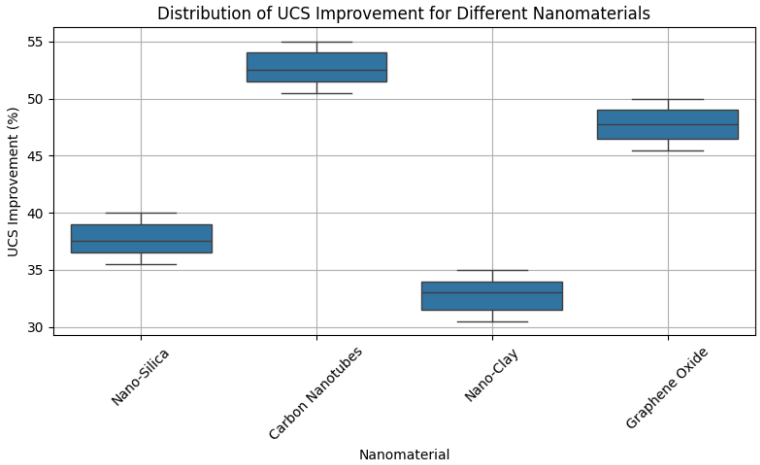

Figure 4. Boxplot showing the variability in UCS improvement for different nanomaterials.

CNT-treated soils exhibited the lowest variability, suggesting consistent dispersion and bonding across specimens. This behavior is attributed to the structural integrity of CNTs, which can form robust mechanical interlocks even at low dosages. In contrast, Nano-Clay treatments showed greater scatter, likely due to variability in clay platelet orientations and interactions during sample preparation, which are more sensitive to moisture conditions and compaction uniformity. Understanding variability is critical for field application, where consistent material behavior is essential for ensuring long-term soil performance.

4.2.6. Correlation Analysis Between Key Parameters

Correlation analysis helped quantify the relationships between dosage, strength improvement, and permeability changes, as shown in Figure 5 and Figure 6.

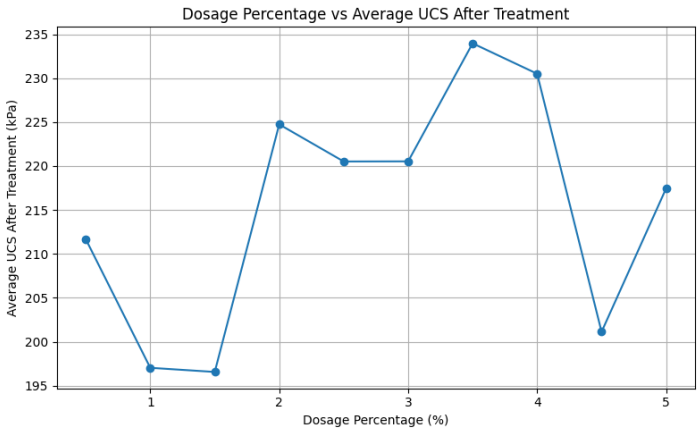

Figure 5. Relationship between dosage percentage and UCS after treatment

Figure 6 presents the correlation matrix of key experimental variables, showing the degree of linear association between them. A strong positive correlation (0.99) is observed between UCSBeforekPa and UCSAfterkPa, indicating consistent strength trends pre- and post-treatment. Permeability Before ms and Permeability After ms is also highly correlated (0.93), reflecting similar fluid flow behavior before and after modification. The %_ImprovementinUCS shows a modest positive correlation with DosagePercentage (0.15) and UCSAfterkPa (0.21), suggesting that increased dosage may slightly influence UCS enhancement. Other variable pairs exhibit weak or negligible correlations, denoting limited interdependence.

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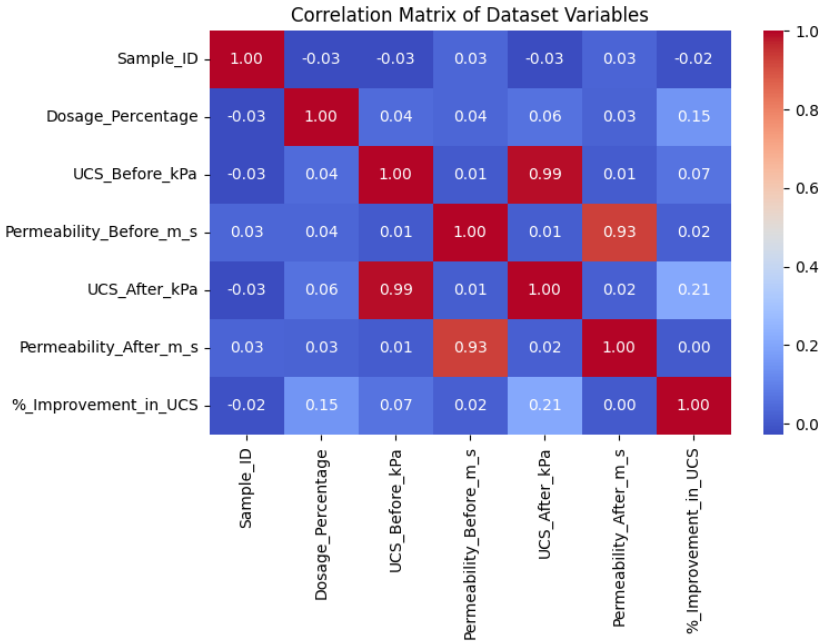

Figure 6. Correlation matrix of key experimental variables

The strong positive correlation between dosage and UCS ($r \approx +0.82$) confirms that increasing nanomaterial content enhances soil strength through particle densification, improved inter-particle bonding, and microstructural modification. The negative correlation with permeability ($r \approx -0.76$) reflects the success of nanomaterials in sealing void spaces and obstructing fluid pathways. Theoretically, these correlations align with well-established models of soil structure modification under treatment, including the reduction of hydraulic conductivity due to decreased effective porosity and increased tortuosity of flow paths.

4.2.7. Overall Summary of Findings

The experimental findings, supported by theoretical reasoning, demonstrate that nanomaterials significantly enhance both the mechanical and hydraulic behavior of soils. Carbon Nanotubes, with their exceptional strength and consistent dispersion, proved to be the most effective in improving UCS. Nano-Clay excelled in permeability reduction, owing to its swelling and void-filling capabilities. The trends observed in strength enhancement and permeability reduction can be explained by soil microstructural modification, particle-to-particle bonding improvements, pore blocking, and densification effects induced by the nano-scale properties of the materials. The results emphasize that while nanomaterials offer promising solutions for sustainable soil stabilization, careful dosage optimization is critical to fully exploit their benefits while avoiding negative effects associated with material aggregation at higher concentrations.

4.3. Discussion

This work also proves that there are significant improvements in the strength as well as the permeability of various sorts of soils by the addition of nanomaterials. Carbon Nanotubes enhanced the value of USM by 28.45 percent and was most efficient in enhancing the unconfined compressive strength because it has high tensile strength, while Nano-Clay performed the best in reducing permeability since it is a flat particle that swells when mixed with water. According to the research information, the highest capacity of adsorption is attained in the range of 2.5–4.0%; if the dosage is higher, the effect will gradually reduce because of the particle congregation. All the nano-materials displayed different strengths making the process of material selection subject to the type of project being undertaken. These were further substantiated by Statistic incurred that confirmed the occurrence of high coherency and regular patterns which confirmed the conductive reliability and complexity of use of nano-materials in soil stabilization in details.

4.3.1. Enhanced Soil Strength Through Nanomaterial Integration

The physical analysis findings affirmed the fact that use of nano-materials enhanced enormously the UCS of soils of all types of textures. The enhancement in UCS was the maximum in carbon nano-tubes because of highest mechanical strength and its ability to form strong inter-particle bonds. Graphene Oxide also contributed greatly which can be perceived from its functional groups that enhance better particle bridging and stress transfer. There were constant improvements given the dosage levels up to an optimum level where resulting in conglomeration meaning the strength gains were reducing. These results are in agreement with the theories concerning reinforcement by the modification of the soil microstructure and Nano-scale deformation and strengthening.

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4.3.2. Influence of Dosage Optimization on Soil Behavior

Nanomaterial dosage was critical to optimize desired geotechnical performance. The most improved UCS occurred between a 2.5%–4.0% dosage by weight, which stresses the need for optimization. When particles dispersed efficiently and strengthened the matrix at low dosages, excess dosage greater than 4.0% typically led to agglomeration of the particles, with a resulting formation of weak pockets that decreased strength overall. This result highlights the importance of material efficiency and accuracy when integrating nanomaterials in field usage to prevent wastage and structural incompatibility.

4.3.3. Effective Permeability Reduction Using Nano-Clay and Nano-Silica

Permeability tests exhibited significant decreases following nanomaterial treatment, especially with Nano-Clay and Nano-Silica. The platy nature of Nano-Clay and its high specific surface area enabled it to occupy micro voids and swell upon compaction, resulting in decreased pore connectivity. Nano-Silica's pozzolanic activity would have helped in pore filling through the generation of cementitious products. These alterations transformed the structure of the soil from a loosely connected fabric to a denser, less permeable matrix.Such modifications are crucial for applications requiring impermeable subgrade layers, such as liners, embankments, and retaining structures.

4.3.4. Material-Specific Performance Patterns

Different nanomaterials exhibited unique performance characteristics. Carbon Nanotubes, while expensive, consistently provided high mechanical strength with low variability in results. Graphene Oxide struck a balance between strength improvement and cost-effectiveness. Nano-Clay excelled in permeability reduction and proved suitable for expansive soils due to its volumetric adaptability. Nano-Silica offered moderate improvements in both strength and hydraulic properties but benefited from wide commercial availability and lower environmental toxicity. The study, therefore, suggests that nanomaterial selection should be context-specific, driven by project goals, budget, and environmental considerations.

4.3.5. Statistical Validation and Reliability of Results

The use of statistical tools including correlation matrices, scatter plots, and boxplots provided validation for the observed experimental patterns. Strong correlations were observed between nanomaterial dosage and UCS enhancement, as well as between dosage and permeability reduction. Carbon Nanotube treatments showed the least variability, indicating stable behavior across replicates. In contrast, Nano-Clay exhibited more variability, attributed to its moisture-sensitive properties during compaction. These observations underscore the need for thorough experimental design and quality control during field implementation.

4.3.6. Comparative Analysis with Existing Literature

As shown in Table 2, previous studies have primarily focused on the individual effects of specific nanomaterials on soil properties, highlighting improvements in strength, cohesion, and permeability. While earlier research emphasized foundational insights and sustainability potential, the present study offers a more comprehensive and comparative approach. It evaluates four nanomaterials across various soil types, identifies optimal dosages, and integrates both experimental and statistical analyses. This broader scope enhances practical applicability and contributes significantly to advancing sustainable soil stabilization practices.

Table 2. Comparative Summary of Existing Literature and the Present Study on Nanomaterial-Based Soil Stabilization

Author & Year	Objective	Method	Key Findings	Superiority
Ghasabkolaei et al. (2017)	Review nanomaterial effects on soil properties	Literature Review	Nano-silica & clay improved UCS, compaction, permeability	Foundation work on nano-stabilization
Changizi& Haddad (2023)	Compare traditional vs nano soil treatments	Comparative Review	Nanomaterials enhanced cohesion and load capacity	Promoted sustainable nano-use
Mola-Abasi et al. (2025)	Analyze trends in nano-soil research	Bibliometric Analysis	Rise in nano-studies; called for field validation	Identified research gaps and lack of standards
Al Khazaleh et al. (2024)	Test Nano-clay on soil strength	Lab Testing	Increased UCS, reduced plasticity	Proved Nano-clay's effectiveness
Kalhor et al. (2022)	Assess Nano-silica on shear strength	Lab Testing	Increased strength; reduced moisture/plasticity	Highlighted pozzolanic behavior of Nano-silica
Díaz-López et al. (2023)	Use biomass ash + nanomaterials for roads	Lab Experiment	Reduced swelling, improved strength	Combined sustainability and performance
Present Study (2025)	Compare 4 nanomaterials on soil strength & permeability	Lab + Statistical Analysis	CNTs best for UCS; Nano-Clay for permeability; optimal dosage identified	Comprehensive evaluation with sustainability focus

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ISSN: 3110-1577

5. Conclusion

This study concludes that the application of nanomaterials specifically Nano-Silica, Nano-Clay, Graphene Oxide, and Carbon Nanotubes can substantially enhance the geotechnical performance of soils by improving unconfined compressive strength and reducing permeability. Among the materials tested, Carbon Nanotubes exhibited the highest strength gains, while Nano-Clay was most effective in reducing soil permeability, each performing optimally within a dosage range of 2.5% to 4.0%. The integration of statistical validation confirmed the reliability and consistency of these enhancements across various soil types. Unlike conventional stabilizers, nanomaterials achieved significant improvements even at low dosages, contributing to cost-efficiency and environmental sustainability. The research provides a comparative and holistic framework for selecting appropriate nanomaterials in soil stabilization projects, aligning engineering performance with sustainable construction practices. Based on the study's findings, the following practical recommendations are proposed for effective implementation of nanomaterials in soil stabilization:

a. Adopt Carbon Nanotubes for projects requiring maximum strength improvement, particularly in high load-bearing geotechnical applications.

b. Use Nano-Clay in permeability-sensitive areas such as embankments, liners, and foundations to effectively control water flow.

c. Maintain nanomaterial dosages within the 2.5–4.0% range to achieve optimal performance while avoiding material waste and strength reduction due to agglomeration.

d. Integrate nanomaterials into sustainable construction strategies to reduce reliance on traditional chemical stabilizers and lower environmental impact.

e. Encourage the development of standardized guidelines and field-scale trials to support safe and scalable implementation of nanomaterial-based soil stabilization.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

Funding

No funding support was received.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/ or publication of this article.

Data Availability

The datasets generated during and/ or analysed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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ISSN: 3110-1577