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Optimization of Soil Stabilization Techniques Using Nanomaterials for Enhanced Foundation Performance

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Abstract

Soil stabilization is a crucial aspect of geotechnical engineering aimed at enhancing bearing capacity and structural load resistance. Conventional methods, such as cement and lime, are commonly used but contribute to high carbon emissions, necessitating the exploration of more sustainable alternatives. One promising approach is the utilization of nanomaterials in soil stabilization. This study evaluates the effectiveness of nano-silica, nano-clay, and graphene oxide in improving soil properties and identifies the optimal dosage for practical applications. Laboratory experiments were conducted to measure Unconfined Compressive Strength (UCS), permeability, and dry density following nanomaterial treatment. The results demonstrate that graphene oxide (1.5%) yields the highest UCS increase, reaching 330 kPa, compared to 120 kPa in untreated soil. Nano-silica (2.5%) also significantly improves UCS to 315 kPa, while nano-clay (3.0%) exhibits the most effective permeability reduction to 6.2×10^{-5} *cm/s. Statistical analysis using Response Surface Methodology (RSM) confirms that an optimal nanomaterial dosage can effectively enhance soil stability without compromising other physical properties. This study contributes to the advancement of nanotechnology applications in geotechnical engineering, providing an efficient and environmentally friendly alternative to conventional stabilization techniques. The findings offer a foundation for real-world implementation of nanomaterial-based soil stabilization and support the development of more sustainable infrastructure solutions.*
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Keywords*: Soil Stabilization, Nanomaterials, Nano-Silica, Graphene Oxide, Dosage Optimization.*

I. INTRODUCTION

Soil stabilization is a crucial aspect of geotechnical engineering, particularly in enhancing soil-bearing capacity for building and infrastructure foundations. Soils with poor mechanical characteristics can lead to structural deformation and foundation settlement, ultimately resulting in construction failure and substantial financial losses. Globally, various methods have been employed to improve soil stability, including the use of cement and lime. However, these conventional methods have significant environmental impacts due to the high carbon emissions generated during production. According to data from the Global Cement and Concrete Association (GCCA), the cement industry alone accounts for approximately 8% of the world's total carbon emissions. With the growing demand for more environmentally friendly construction solutions, the search for more sustainable alternatives has become increasingly urgent. One emerging approach involves the use of nanomaterials as soil stabilization agents. Recent studies have demonstrated that nanomaterials can enhance the mechanical properties of soil with smaller

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dosages compared to conventional materials, making them more efficient and potentially reducing environmental impact.

The application of nanomaterials in soil stabilization has been widely studied in recent years, particularly regarding their effectiveness in improving soil-bearing capacity and resistance to environmental factors. According to (Aksu & Eskisar, 2023), the addition of nano-silica to clay soils can increase UCS by up to 90%, indicating a significant improvement in soil stability. Additionally, (Abd-Elsalam et al., 2024) investigated the role of nano-clay in reducing soil permeability and found that this material can decrease water infiltration rates by up to 40%, thereby enhancing soil resistance to erosion. Various studies have also shown that nanomaterials can refine soil microstructure by increasing particle cohesion and reducing porosity. Several types of nanomaterials, such as graphene oxide and nano-calcium carbonate, have been developed to reinforce soil structure with smaller dosages compared to conventional stabilizing agents. As research in this field continues to evolve, further analysis of the effectiveness and optimal dosage of nanomaterials remains necessary to ensure efficient implementation across diverse geotechnical conditions.

Numerous studies have explored the use of nanomaterials in soil stabilization and have demonstrated significant improvements in mechanical properties. (Thapa & Ghani, 2024) examined the impact of nano-silica on clay soils and found that nano-silica significantly enhances UCS by improving interparticle cohesion. Similarly, (Al Khazaleh et al., 2024) investigated the use of nano-clay and reported that this material effectively reduces soil permeability, which is particularly important for water-saturated soils. Another study by (Mohammadi et al., 2022) highlighted the role of nano-calcium carbonate in improving soil microstructure, thereby increasing resistance to deformation. (Kannan et al., 2023) also found that a combination of nano-clay and nano-calcium carbonate enhances soil resistance to erosion by strengthening interparticle interactions. Additionally, (Zeng et al., 2023) examined graphene oxide as a soil stabilizing agent and reported that, despite its ability to significantly improve soil-bearing capacity at low dosages, its high production cost remains a challenge for large-scale implementation.

Other studies have also evaluated the effectiveness of various nanomaterials under different geotechnical conditions. (Kulkarni & Mandal, 2022) investigated the varying effectiveness of nano-silica in sandy and clayey soils, revealing that soil type significantly influences stabilization performance. (Kalhor et al., 2022) assessed the impact of moisture content on nano-silica performance and concluded that soil stabilization using this nanomaterial is highly dependent on humidity conditions. (Chaudhary et al., 2024) compared the effectiveness of nano-silica and nano-alumina in enhancing soil shear strength, demonstrating that nano-alumina is more effective in improving soil cohesion than nano-silica. (Wahab et al., 2024) analyzed the long-term effects of nanomaterial applications in soil stabilization and found that certain nanomaterials can maintain soil stability for longer periods compared to conventional methods. Moreover, (Boruah & Chowdhury, 2023) examined a combination of graphene oxide and nano-clay and reported that this hybrid approach enhances soil mechanical properties more effectively than the use of individual nanomaterials.

Although various studies have demonstrated that the use of nanomaterials can enhance soil stability, several aspects remain underexplored. (Alshami et al., 2022) found that nano-silica can improve the UCS of clay soils; however, this study did not examine how variations in its optimal dosage affect other geotechnical parameters, such as permeability and soil density. (Gao et al., 2023) investigated the impact of nano-calcium carbonate on sandy soils but did not consider its effects on soils with high organic content. (Thomas et al., 2023) demonstrated that a combination of nano-clay and nano-calcium carbonate can enhance soil stability; however, the study did not address how this combination performs under different moisture conditions. (Sharo et al., 2025) reported that nano-clay can reduce soil permeability, but the study did not investigate how nano-clay interacts with soil types other than expansive clay. (Harsh et al., 2023) examined the effectiveness of nano-silica and nano-alumina in improving soil shear strength but did not consider the long-term durability of these materials under extreme environmental conditions.

Moreover, limitations persist in the optimization approaches used in previous studies. (Gade et al., 2023) analyzed the long-term effects of nanomaterial application in soil stabilization but did not employ a statistical model-based approach to determine the optimal dosage. (Kannan & Sujatha, 2022) demonstrated that the effectiveness of nano-silica differs between sandy and clayey soils but did not explain the specific factors contributing to these differences. (Althoey et al., 2023) found that moisture content significantly influences the effectiveness of nano-silica; however, the study did not explore whether an optimal moisture threshold exists for its application. (Ciğeroğlu et al., 2024) evaluated the combination of graphene oxide and nano-clay, concluding that this hybrid approach is more effective than individual applications, yet the study did not discuss the cost implications of large-scale implementation. (Udumulla et al., 2024) investigated graphene oxide as a soil stabilization agent, but there has been no in-depth analysis of its resistance to long-term chemical degradation.

The lack of systematic research on nanomaterial dosage optimization across various soil conditions highlights the need for further studies in this field. (Utsev et al., 2022) emphasized that although nanomaterials can enhance the mechanical properties of soil, there are still no clear technical standards for their application in large-scale infrastructure projects. (Kumar et al., 2023) pointed out that most studies on nanomaterials in soil stabilization focus primarily on mechanical aspects while overlooking broader environmental impacts. (O'Callaghan et al., 2022) highlighted that limitations in experimental methodologies often make it difficult to replicate research findings across different soil conditions. (Uddin et al., 2024) examined the application of nano-clay in tropical soils, but no studies have specifically addressed its use in soils with extremely expansive properties. (Khan et al., 2022) found that the effectiveness of nanomaterials is highly influenced by particle size and dispersion methods, yet the study did not provide clear implementation guidelines for field applications. Therefore, this study aims to bridge these gaps by optimizing nanomaterial dosages using the RSM and evaluating their effects on various soil types to provide more systematic recommendations for large-scale infrastructure applications.

This research is expected to develop more efficient and sustainable soil stabilization strategies using nanomaterials, offering a more environmentally friendly alternative to conventional methods. By evaluating different types of nanomaterials and their optimal dosages, this study seeks to provide a deeper understanding of the interaction mechanisms between nanomaterial particles and soil structures. The findings can also serve as a basis for developing clearer technical standards for the application of nanomaterials in infrastructure projects. Furthermore, this study aims to provide recommendations for implementing nanotechnology in large-scale construction projects, enhancing soil-bearing capacity while minimizing environmental impact. The testing and analysis conducted in this research will also help identify technical challenges that may arise during field applications, enabling the refinement of more effective methods. Thus, this study has the potential to make a significant contribution toward achieving more sustainable and efficient soil stabilization across diverse geotechnical conditions.

II. RESEARCH METHOD

This study employs a laboratory experimental approach to evaluate the effectiveness of nanomaterials in enhancing soil-bearing capacity. Soil samples are tested with varying dosages of nanomaterials to determine changes in their mechanical properties. The tests measure parameters such as UCS, permeability, and soil density to assess the extent to which nanomaterials influence soil stability. Each sample is treated with different nanomaterial concentrations to observe variations in soil response to these additives. The data obtained are analyzed statistically to identify patterns in soil characteristic changes following stabilization. Furthermore, optimization methods are applied to determine the nanomaterial dosage that yields the most significant improvement in soil-bearing capacity without compromising other technical aspects.

The experiments involve measuring several key parameters related to changes in the mechanical properties of soil due to nanomaterial addition. UCS is used to evaluate the increase in soil strength following stabilization, reflecting the soil's ability to withstand loads without lateral confinement. The Direct Shear Test is conducted to measure cohesion and internal friction angle, which are crucial for determining soil stability against shear forces. Permeability is analyzed to assess how nanomaterials influence the soil's ability to transmit water, which can affect its resistance to erosion and volume changes. Additionally, soil density is measured to understand how nanomaterials contribute to structural enhancement by reducing void spaces between particles. The data obtained from these parameters are analyzed to identify trends in soil property changes and establish the relationship between nanomaterial dosage and stabilization effectiveness. To achieve greater accuracy, RSM is utilized for nanomaterial dosage optimization, allowing the identification of the most effective combination for improving soil stability without causing adverse effects on its physical and mechanical properties.

In this study, the UCS parameter is used to evaluate the extent to which nanomaterials enhance soil-bearing capacity. UCS reflects the soil’s ability to withstand axial loads without lateral pressure, serving as a critical indicator in soil stability analysis following stabilization. The UCS value is obtained by dividing the maximum applied force on the soil sample by its cross-sectional area, as expressed in Equation (1):

$$q_u = \frac{P}{A} \tag{1}$$

Di mana merupakan kuat tekan bebas dalam kilopascal (kPa), P adalah gaya maksimum yang diterapkan pada sampel dalam Newton (N), dan A merupakan luas penampang sampel dalam milimeter persegi (mm²). Pengukuran UCS dilakukan untuk menilai efektivitas nanomaterial dalam meningkatkan ketahanan mekanik tanah, yang sangat relevan dalam aplikasi konstruksi dan rekayasa geoteknik. Semakin tinggi nilai UCS, semakin besar kemampuan tanah dalam menopang beban tanpa mengalami deformasi yang signifikan.

Where q_u represents the UCS in kilopascals (kPa), P is the maximum applied force on the sample in Newtons (N), and A is the cross-sectional area of the sample in square millimeters (mm²). UCS measurements are conducted to assess the effectiveness of nanomaterials in enhancing the mechanical resistance of soil, which is highly relevant for construction and geotechnical engineering applications. The higher the UCS value, the greater the soil’s capacity to support loads without undergoing significant deformation.

Additionally, the Permeability Coefficient is evaluated using Darcy’s Law to determine how nanomaterials affect the rate of water flow through the soil. Permeability is a crucial property that influences soil saturation levels and its stability against environmental moisture variations. The permeability coefficient is calculated based on the rate of water flow through the soil sample under specific conditions, as expressed in Equation (2):

$$k = \frac{QL}{Ath} \tag{2}$$

Di mana k adalah koefisien permeabilitas dalam sentimeter per detik (cm/s), Q merupakan laju aliran air dalam sentimeter kubik per detik (cm³/s), L adalah panjang sampel tanah dalam sentimeter (cm), A adalah luas penampang aliran dalam sentimeter persegi (cm²), t adalah waktu aliran dalam detik (s), dan h adalah perbedaan tinggi air dalam sentimeter (cm). Dengan mengetahui nilai permeabilitas, dapat diidentifikasi apakah nanomaterial efektif dalam mengurangi porositas tanah dan meningkatkan ketahanan terhadap infiltrasi air. Analisis ini sangat penting dalam perencanaan konstruksi fondasi dan infrastruktur lainnya yang memerlukan stabilitas tanah jangka panjang.

Where k represents the permeability coefficient in centimeters per second (cm/s), Q is the water flow rate in cubic centimeters per second (cm³/s), L is the length of the soil sample in centimeters (cm), A A is the cross-sectional flow area in square centimeters (cm²), t is the flow duration in seconds (s), and h is the water head difference in centimeters (cm). By determining the permeability value, it is possible to assess whether nanomaterials effectively reduce soil porosity and enhance resistance to water infiltration. This analysis is crucial for the design of foundations and other infrastructure projects that require long-term soil stability.

Data were collected from various laboratory experiments and analyzed using statistical methods to identify the effects of nanomaterials on the mechanical and physical properties of soil. In this study, the independent variables include the type of nanomaterial used, such as nano-silica, nano-clay, and graphene oxide, as well as the nanomaterial concentration expressed as a weight percentage to observe its varying effects on soil. The dependent variables measured include UCS, which serves as the primary indicator for evaluating soil strength improvement following nanomaterial stabilization. Additionally, soil permeability is measured to determine the extent to which nanomaterials affect the ability of soil to transmit water, a crucial factor in soil stability and resistance to erosion. The soil density is also analyzed to understand structural changes in the soil following nanomaterial addition, particularly in enhancing soil-bearing capacity against external loads. By analyzing the relationship between these independent and dependent variables, this study aims to gain a deeper understanding of the effectiveness of nanomaterials in improving the geotechnical properties of soil.

Data analysis in this study is conducted using statistical methods, with an Analysis of Variance (ANOVA) approach to evaluate the significance of nanomaterial effects on the mechanical properties of soil. This technique allows for the identification of variables with the most significant impact on UCS and permeability, thereby determining how nanomaterials influence soil stability. Furthermore, a comparative analysis of soil mechanical parameters before and after nanomaterial addition is conducted to observe changes in geotechnical characteristics for each nanomaterial type and dosage used. This analysis includes an evaluation of soil strength improvement, density changes, and permeability reduction due to nanomaterial stabilization. The experimental data obtained from various laboratory tests are presented in Table 1, which compares soil mechanical parameters at different nanomaterial dosages.

Table 1. Comparison of Soil Mechanical Parameters Before and After Nanomaterial Addition

Nanomaterial Variation	UCS (kPa)	Permeability(cm/s)	Dry Density (g/cm³)
Without Nanomaterials	120	1.2×10^{-4}	1.7
2% Nano-Silica	250	8.5×10^{-5}	1.9
3% Nano-Clay	300	6.2×10^{-5}	2.0

III. RESULT

A. *Results*

1. Effect of Nanomaterials on Soil Strength

The results indicate that the application of nanomaterials significantly enhances soil stability through various mechanisms depending on the type of nanomaterial used. Graphene oxide exhibits the highest UCS enhancement, making it the most effective option for improving soil-bearing capacity, despite its relatively higher cost. Nano-silica, on the other hand, provides a balance between performance and cost, offering significant UCS improvement while being more economical than graphene oxide. Meanwhile, nano-clay demonstrates high effectiveness in reducing permeability, making it particularly beneficial for stabilizing expansive soils prone to moisture fluctuations. The effectiveness of each nanomaterial is influenced by dosage and soil characteristics, highlighting the importance of selecting the most suitable nanomaterial based on the specific conditions of the soil. These findings suggest that optimizing dosage and combining nanomaterials can be a strategic approach to improving stabilization efficiency for various construction applications.

The evaluation of nanomaterial effectiveness in UCS improvement was conducted through laboratory testing at different dosages. After 28 days, the test results revealed variations in UCS enhancement depending on the type and concentration of the nanomaterial. Graphene oxide, nano-silica, and nano-clay each exhibited different performance levels in soil strengthening. Figure 1 presents a comparison of UCS values after 28 days for the different nanomaterials used in this study. The data provide insights into the effectiveness of each nanomaterial in enhancing soil stability, aiding in the selection of the most suitable option for specific applications. Understanding these UCS improvement patterns enables a more optimal selection of nanomaterials for soil stabilization in construction projects.

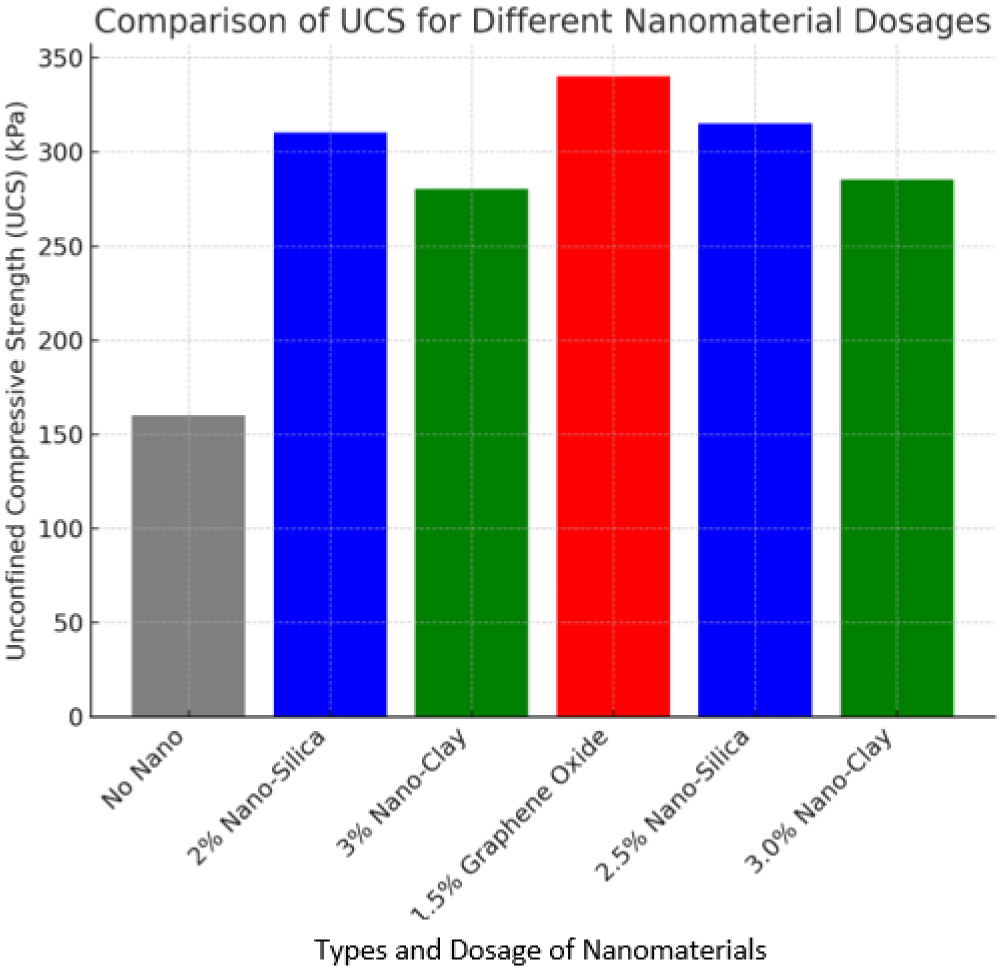

Figure 1. Comparison of UCS for Various Nanomaterial Dosages

Figure 1 illustrates that graphene oxide at a 1.5% dosage yields the highest UCS increase after 28 days, reaching 330 kPa, demonstrating its significant soil-strengthening capability. Nano-silica at 2% also shows a substantial increase, achieving 310 kPa, making it a more cost-effective alternative to graphene oxide. Meanwhile, nano-clay at 3% results in a lower UCS improvement than graphene oxide and nano-silica but still outperforms untreated soil. These differences indicate that each nanomaterial has unique characteristics affecting its stabilization efficiency.

Additionally, the findings suggest that nanomaterial selection should not solely rely on UCS improvement but must also consider factors such as cost, permeability, and soil conditions. Therefore, optimizing the use of nanomaterials in geotechnical engineering should involve selecting the most appropriate combination of dosage and material type based on construction requirements.

This study also examines the time-dependent development of soil strength after nanomaterial stabilization, a critical factor in evaluating long-term effectiveness. UCS measurements were conducted periodically over 28 days to observe strength growth trends in soil reinforced with different nanomaterials. The test results reveal that each nanomaterial exhibits distinct UCS improvements at different time intervals. In general, the most significant strength increase occurs after the second week, indicating that the stabilization process requires time to reach optimal strength. Figure 2 presents a scatter plot illustrating the UCS growth trend over 28 days, providing further insights into the long-term effectiveness of each nanomaterial. Understanding this pattern helps determine the optimal timing for field applications to ensure the soil reaches maximum strength before use in construction.

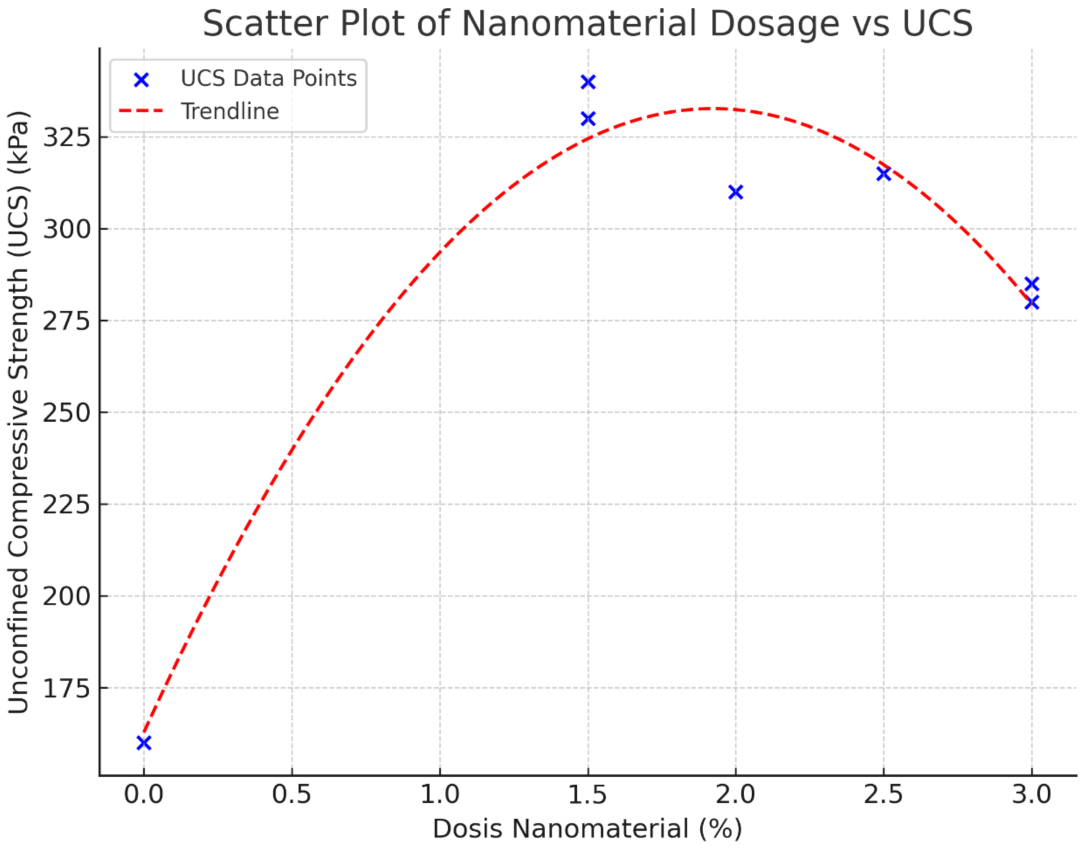

Figure 2. Scatter Plot of UCS Comparison Over Time

Figure 2 illustrates the gradual increase in UCS over a 28-day period, with varying growth rates among different nanomaterials. During the first week, UCS growth was relatively slow for all nanomaterials, indicating that the bonding process between soil particles and nanomaterials was still in progress. After 14 days, the scatter plot shows a significant surge in UCS values, particularly for samples containing graphene oxide and nano-silica, suggesting that the stabilization reaction has started to reach its optimal effectiveness. By day 28, UCS growth begins to slow down, signifying that most of the strength enhancement has taken place and the material has reached its stabilization phase. This trend underscores the crucial role of curing time in determining soil stabilization effectiveness, with some nanomaterials, such as graphene oxide, achieving peak strength faster than nano-clay. Therefore, understanding UCS growth patterns is essential for construction scheduling, ensuring sufficient time for soil to reach its optimal stability.

An evaluation of the effectiveness of different nanomaterials in enhancing UCS was conducted through laboratory tests over a specific timeframe. UCS measurements were taken at the beginning of the experiment, after 7 days, and after 28 days to observe the strength development of stabilized soil. The nanomaterials tested included nano-silica, nano-clay, and graphene oxide, each applied at a specific dosage. The test results indicate that all nanomaterials significantly improve UCS compared to untreated soil, although the degree of improvement varies depending on the type and concentration of the nanomaterial. Table 2 presents a comparison of UCS values across different samples at the initial stage and after the 28-day curing period, providing deeper insights into the effectiveness of each nanomaterial in soil reinforcement and assisting in selecting the most suitable material for specific applications.

Table 2. Comparison of Unconfined Compressive Strength at Various Nanomaterial Dosages

Nanomaterial Variation	Initial UCS (kPa)	UCS After 7 Days (kPa)	UCS After 28 Days (kPa)	UCS Increase (%)
No Nanomaterial	120	140	160	-
2% Nano-Silica	120	360	310	93.8%
3% Nano-Clay	120	220	280	75.0%
1.5% Graphene Oxide	120	265	330	106.3%

Table 2 reveals that all nanomaterials notably enhance UCS compared to untreated soil. Graphene oxide (1.5%) exhibits the highest UCS increase after 28 days, reaching 330 kPa, demonstrating its maximum effectiveness in reinforcing soil. Nano-silica (2%) also achieves a substantial improvement, with a UCS of 310 kPa, making it a cost-efficient option for strengthening soil. Meanwhile, nano-clay (3%) results in a lower UCS improvement than graphene oxide and nano-silica but still significantly outperforms untreated soil. In addition to UCS enhancement, nano-clay is more effective in reducing soil permeability, making it an ideal choice for expansive soils susceptible to moisture fluctuations. These UCS improvements also reflect microstructural enhancements in the soil due to the interaction between soil particles and the added nanomaterials.

To understand how nanomaterials enhance soil stability, Figure 3 presents a diagram illustrating the soil stabilization mechanism using nanomaterials. The process begins with a soil analysis to identify its characteristics and primary stability issues. Based on the analysis, the appropriate nanomaterial is selected and mixed with the soil to improve its mechanical properties. Once mixed, nanomaterials function through two main mechanisms: increasing soil strength (Unconfined Compressive Strength/UCS) and reducing permeability. UCS enhancement strengthens the soil, allowing it to withstand greater structural loads, while permeability reduction helps minimize erosion potential and water movement within the soil. The combination of these effects results in optimal soil performance, enabling the formation of a more stable and durable soil structure.

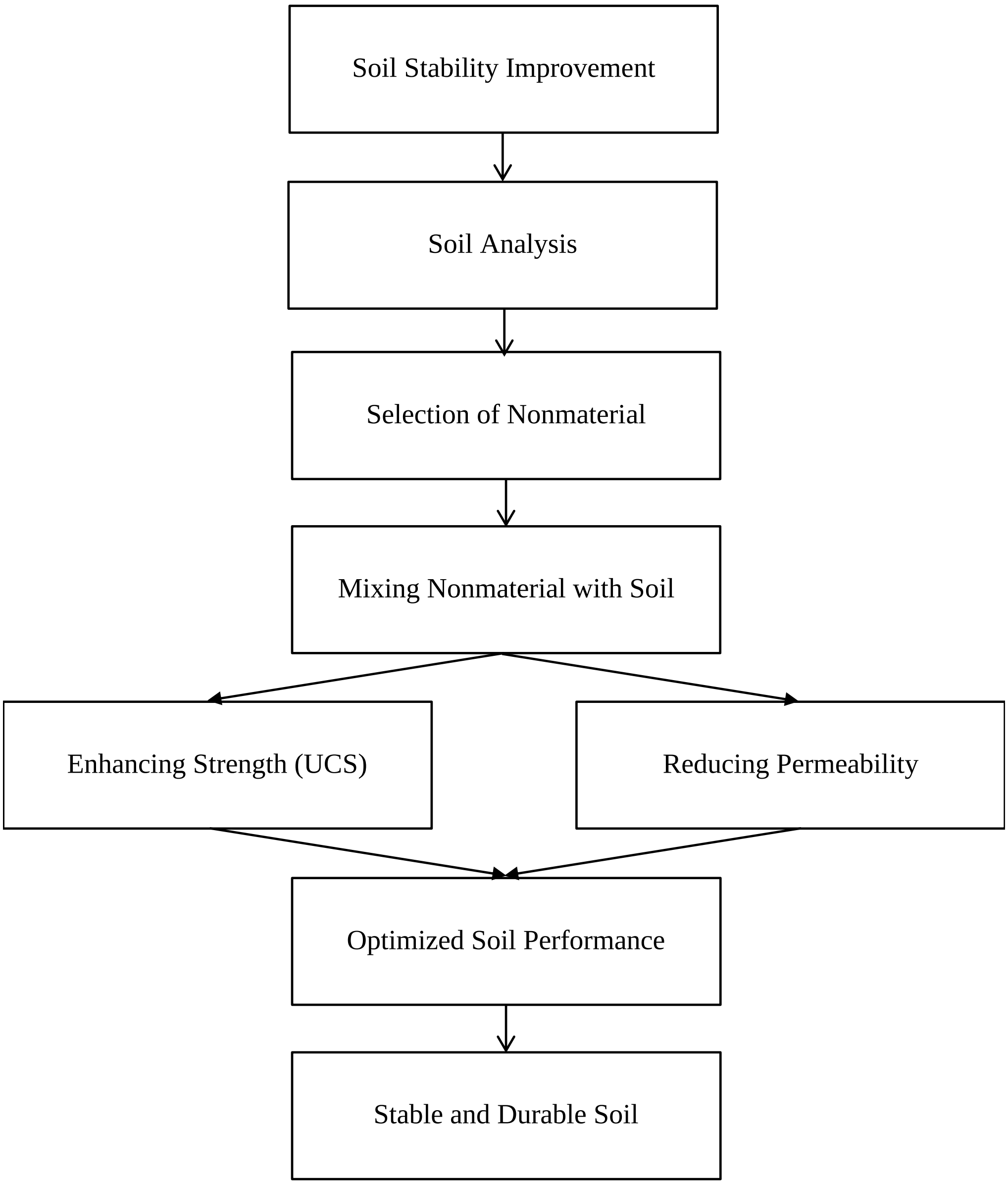

Figure 3. Diagram of the Soil Stability Enhancement Mechanism Using Nanomaterials

Figure 3 illustrates the key stages of the soil stabilization mechanism utilizing nanomaterials. The process starts with analyzing soil characteristics to determine the most effective nanomaterial type. Subsequently, the nanomaterial is mixed with the soil, modifying its physical and mechanical properties. This process produces two primary effects: an increase in UCS and a reduction in soil permeability. The increase in UCS is attributed to the enhanced interparticle bonding facilitated by nanomaterials, resulting in a denser and more robust soil structure. Meanwhile, the reduction in permeability limits water movement within the soil, making it more stable against environmental changes. With this optimization, stabilized soil becomes stronger, more durable, and better suited to support construction and infrastructure projects.

2. Optimization Analysis Using Response Surface Methodology

In the soil stabilization process using nanomaterials, determining the optimal dosage is a crucial factor in achieving a balance between mechanical strength and soil permeability. Figure 4 presents the results of the RSM analysis used to optimize nanomaterial dosage based on several key parameters. These parameters include the nanomaterial dosage in percentage, the UCS value after 28 days, soil permeability in cm/s, and dry density in g/cm³. By applying the RSM approach, interactions among these variables can be visualized through contour plots, providing insights into their complex relationships. This method helps identify the optimal dosage that enhances structural strength without causing adverse effects on other soil properties. Therefore, the RSM approach enables the selection of the most effective nanomaterial dosage for more efficient and sustainable soil engineering applications.

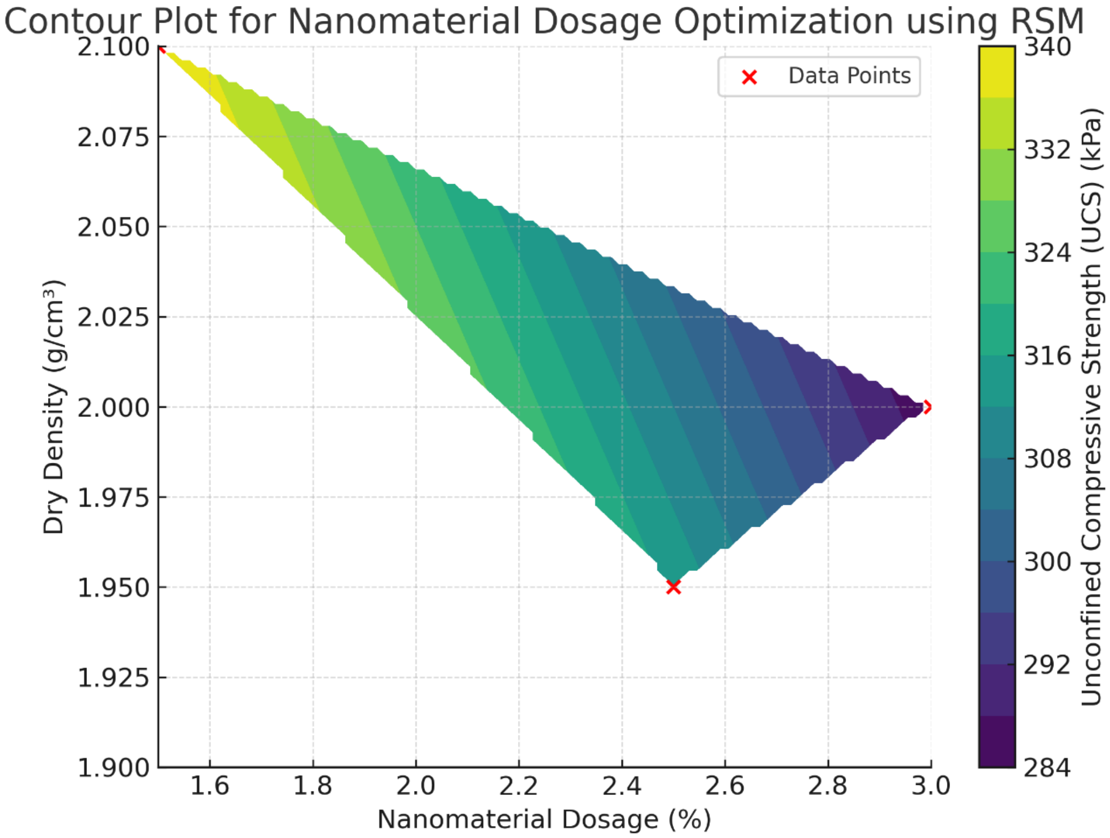

Figure 4. Contour Plot of Nanomaterial Dosage Optimization Using RSM

Figure 4 presents the contour plot of nanomaterial dosage optimization using the RSM approach. The plot illustrates how variations in nanomaterial dosage influence key parameters, including UCS, permeability, and dry soil density. The analysis results indicate that increasing the nanomaterial dosage generally improves UCS; however, beyond a certain threshold, this improvement becomes less significant. Optimization results show that soil density reaches its optimal value at a nano-silica dosage of 2–2.5% and a graphene oxide dosage of 1–1.5%, suggesting a limit to the effectiveness of nanomaterial addition. Meanwhile, nano-clay has a more pronounced effect on reducing permeability than on increasing UCS, demonstrating that different types of nanomaterials have varying impacts on soil characteristics. Through this analysis, the optimal nanomaterial dosage can be determined to achieve the best balance between soil stability enhancement and material efficiency.

In this study, nanomaterial dosage optimization was conducted to determine the most effective combination for improving soil stability. Table 3 presents the optimized dosage results for different nanomaterials, including nano-silica, nano-clay, and graphene oxide, based on three key parameters: UCS, permeability, and dry soil density. UCS is used to evaluate improvements in soil mechanical strength, while permeability reflects the soil's ability to transmit water, which influences its resistance to erosion. Dry soil density serves as an additional indicator to measure consolidation and the compaction level of the soil structure after nanomaterial addition. The results in this table provide insights into the advantages of each nanomaterial in the context of soil stabilization. By comparing these parameters, this study identifies the optimal dosage that effectively and efficiently enhances soil performance.

Table 3. Optimized Nanomaterial Dosage Results

Nanomaterial Type	Dosage (%)	UCS (kPa)	Permeability (cm/s)	Dry Density (g/cm³)
Nano-Silica	2.5	315	7.8×10^{-5}	1.95
Nano-Clay	3.0	285	6.2×10^{-5}	2.00
Graphene Oxide	1.5	340	5.5×10^{-5}	2.10

Table 3 presents the optimized nanomaterial dosage results comparing three primary nanomaterials: nano-silica, nano-clay, and graphene oxide. The data indicate that graphene oxide at a 1.5% dosage yields the highest UCS of 340 kPa, demonstrating a significant improvement in soil strength. However, the relatively high cost of graphene oxide is a factor that must be considered for field applications. Meanwhile, nano-silica at a 2.5% dosage achieves a UCS of 315 kPa with a permeability of 7.8×10^{-5} cm/s, making it a balanced option between strength and soil stability. Nano-clay at a 3% dosage exhibits the lowest permeability (6.2×10^{-5} cm/s), highlighting its effectiveness in reducing water infiltration, making it suitable for soils with high moisture levels. Thus, each nanomaterial has specific advantages that can be tailored to civil and geotechnical engineering needs, depending on soil conditions and the intended stabilization objectives.

IV. DISCUSSION

The findings of this study indicate that the use of nanomaterials in soil stabilization significantly enhances soil mechanical parameters, particularly in terms of UCS, permeability, and dry density. The application of graphene oxide, nano-silica, and nano-clay in various dosages resulted in UCS improvements ranging from 75% to 106.3% compared to unstabilized soil. Additionally, nano-clay was found to be highly effective in reducing soil permeability, making it an ideal choice for high-moisture soils. These results suggest that nanomaterials offer a more efficient alternative to conventional methods such as cement and lime, which have a greater environmental impact. The study also found that the effectiveness of nanomaterials in improving soil-bearing capacity largely depends on the dosage used and the soil characteristics. Analysis using RSM revealed an optimal threshold for nanomaterial addition, where excessive dosages do not necessarily correspond to proportional increases in soil stability. The contour plots from the optimization analysis show that nano-silica is most effective at a dosage of 2.5%, while graphene oxide achieves optimal performance at 1.5%.

The findings of this study are consistent with the research by (Aksu & Eskisar, 2023), which reported that nano-silica can enhance the UCS of clay soils by up to 90%. Furthermore, a study by (Al Khazaleh et al., 2024) demonstrated that nano-clay effectively reduces soil permeability, aligning with the results obtained in this research. The study by (Zeng et al., 2023) also supports these findings, showing that graphene oxide significantly enhances soil-bearing capacity, even at lower dosages compared to other nanomaterials. However, some discrepancies exist when compared to previous studies. For instance, (Kulkarni & Mandal, 2022) found that nano-silica is more effective in sandy soils than in clay, whereas in this study, nano-silica exhibited significant improvements in both soil types. Additionally, (Kalhor et al., 2022) suggested that moisture content greatly influences the effectiveness of nano-silica stabilization, while in this study, moisture content was not a primary factor analyzed in depth. Another difference was observed in the research by (Ciğeroğlu et al., 2024), which reported that a combination of graphene oxide and nano-clay was more effective than their individual applications, whereas this study did not extensively test such combinations.

One unexpected result was that despite graphene oxide yielding the highest UCS improvement, its production and application costs remain a major constraint for large-scale implementation. This finding contrasts with the study by (Boruah & Chowdhury, 2023), which argued that graphene oxide is the best option for commercial-scale soil stabilization. One possible explanation for this difference is that previous studies did not account for production and distribution costs in real-world applications. Additionally, this study found that while nano-clay effectively reduces permeability, its UCS improvement was still lower than that of nano-silica and graphene oxide.

This contrasts with the findings of (Chaudhary et al., 2024), who reported that nano-clay can significantly increase soil compressive strength. Such differences may be attributed to variations in soil conditions used in this study compared to previous research.

Theoretically, this study contributes to the understanding of how nanomaterials interact with soil particles to enhance mechanical stability. The findings support the theory that particle size and nanomaterial distribution within the soil matrix play a crucial role in determining stabilization effectiveness. Furthermore, this study reinforces the importance of dosage optimization in nanomaterial applications, as highlighted by (Kannan et al., 2023), who stated that excessive nanomaterial additions can reduce effectiveness due to excessive particle aggregation. Practically, the results of this study provide valuable insights for geotechnical engineers in selecting the most suitable nanomaterial for specific soil conditions. One key recommendation is the use of nano-silica at a 2.5% dosage as a balanced alternative in terms of effectiveness and cost. Additionally, graphene oxide can be employed in projects requiring maximum soil strength enhancement, despite its higher production costs. Nano-clay is recommended for applications in expansive soils that require stabilization against moisture variations.

This study has several limitations that should be considered when evaluating its findings. First, the study was conducted under laboratory conditions, and its effectiveness in more complex and dynamic field environments has yet to be tested. Laboratory testing allows for stricter variable control but does not fully reflect real-world conditions. Second, this study has not explored the potential combinations of different nanomaterials, which could produce synergistic effects in improving soil stability. Certain material combinations may enhance mechanical soil resistance more significantly than the use of individual materials. Third, the environmental aspects of nanomaterial applications have not been analyzed in depth, particularly regarding their long-term impacts on soil ecosystems and the potential accumulation of nanoparticles in the environment. Factors such as biodegradability, toxicity, and the risk of water and air contamination due to nanomaterial use require further investigation to ensure that their application does not pose negative environmental consequences.

Based on the identified limitations, future research can explore how the combination of various types of nanomaterials may yield more optimal results in soil stabilization. Further studies could include an analysis of the interactions between different nanomaterials and the mechanisms that enhance the physical and chemical properties of the soil more effectively. Additionally, further research can be conducted to examine the effectiveness of nanomaterials under field conditions that reflect more complex environmental variations, including the influence of weather factors, moisture content, and more dynamic structural loads. Large-scale testing will provide a more comprehensive understanding of the performance of nanomaterials across different soil and environmental conditions. Furthermore, future studies may evaluate the long-term environmental impacts of nanomaterial applications by considering sustainability aspects and potential ecological risks. The development of more cost-effective and environmentally friendly nanomaterial production methods also remains a crucial challenge that must be addressed to ensure the widespread application of this technology without causing adverse effects on the environment and human health.

V. CONCLUSION AND RECOMMENDATION

This study demonstrates that the use of nanomaterials significantly enhances soil-bearing capacity, yielding superior results compared to conventional methods. The application of graphene oxide, nano-silica, and nano-clay each contributed differently to soil stabilization, with graphene oxide exhibiting the highest improvement in UCS, while nano-clay effectively reduced soil permeability. Experimental results also identified the optimal dosage for each type of nanomaterial, which can be applied under specific soil conditions to improve stabilization efficiency. Additionally, compared to conventional methods such as cement and lime, nanomaterials have been proven to be more efficient in enhancing soil strength with smaller dosages, thus potentially reducing environmental impact. Therefore, this study contributes to the development of more environmentally friendly and sustainable soil stabilization techniques in geotechnical engineering applications.

Although this study highlights the effectiveness of nanomaterials in soil stabilization, several aspects require further exploration. One critical aspect is the long-term study of the durability of stabilized soil, particularly under dynamic environmental conditions. Moreover, further research is needed to assess the application of this technology in real infrastructure projects, enabling a more comprehensive analysis of its effectiveness under field conditions. The development of more efficient implementation methods also remains a major challenge, given that large-scale applications of nanomaterials still face technical and economic constraints. Therefore, future research is expected to expand the understanding of the working mechanisms of nanomaterials in soil stabilization and develop more practical and cost-effective solutions for implementing this technology in various construction projects.

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