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Research paper

Nanomaterial-Enhanced Stabilization of Soft Clayey Soils: Optimal Content, Mechanical Performance, and Practical Frameworks

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Abstract

Soft clayey soils, characterized by low shear strength and high compressibility, present significant challenges for construction and infrastructure development. This review synthesizes current research on the application of nanomaterials such as nano-clay, nano-silica, and nano-Titanium dioxide (TiO_2) in enhancing the engineering performance of clayey soils. Emphasis is placed on identifying optimal nanomaterial contents and their corresponding effects on both mechanical and physical properties. Owing to their high surface-to-volume ratios and strong interparticle interaction potential, nanomaterials have demonstrated substantial improvements in soil stabilization, including increased compressive strength, reduced plasticity, and enhanced compaction characteristics. Experimental studies report optimal dosages ranging from 0.25% to 7% by dry soil weight, with notable enhancements often achieved at contents below 1%. Improvements are observed in key mechanical parameters such as cohesion, internal friction angle, and California Bearing Ratio (CBR), as well as in physical properties including liquid limit, plastic limit, and dry density. Nano-Silica, nano-clay, and nano-Titanium dioxide are particularly effective in reducing plasticity and increasing strength, while synergistic use with lime or other stabilizers yields further gains. The findings underscore the importance of tailoring nanomaterial type and dosage to specific soil conditions, thereby reducing reliance on trial-and-error approaches.

Keywords*: Nanomaterials, Clayey Soil, Soil Improvement, Mechanical Properties, Physical Properties*

Abbreviations

Al_2O_3	Aluminum oxide
C	Average Cohesion
$CaCO_3$	Calcium Carbonate
CBR	California Bearing Ratio
CuO	Copper Oxide
MC	Moisture content
NNI	National Nanotechnology Initiative
LL	Liquid limit
MgO	Magnesium oxide
OECD	Organization for Economic Co-operation and Development
PI	Plasticity index
PL	Plastic limit
R	Correlation coefficient to measure the strength of a linear relationship between variables
R^2	Coefficient of determination in statistics
SiO_2	Silicon dioxide
TiO_2	Titanium dioxide
UCS	Unconfined compressive strength
WPMN	OECD Working Party on Manufactured Nanomaterials

1. Introduction

Soft soils, with high water content near the liquid limit, exhibit substantial settlement potential and low shear strength [1]. Achieving steady state conditions is critical to meeting construction and post-settlement requirements. Civil engineering projects on such soils have prompted various improvement techniques [2], with growing attention to nanomaterial incorporation [3–6]. Nanoparticles, even in small amounts, significantly alter material properties due to their high interaction potential, leading to their increasing use in geotechnical applications.
Recent reviews address nanoparticles used in soil stabilization, soil structure, and related fields. It was found that the resulting soil structure depends strongly on nanoparticle type and dosage [7]. Another work, [8], reviewed nanomaterial activity across soil types, while another, [9], examined nanoparticle contributions to soil strength by classification. Authors on Ref [10] discussed geotechnical applications, and [11] evaluated locally produced nanoparticles (lime, silica, clay) in Iraq, though optimal percentages were not determined. Fig. 1 presents a conceptual interpretation for the nanomaterial's effects on soil properties.

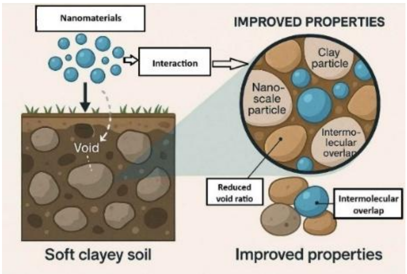


Fig. 1: Effects of nanomaterials on soil properties.

Current experimental studies on soil stabilization with nanomaterials lack a systematic framework for determining optimal nanoparticle dosage based on soil and particle type. Such optimization would guide future research, reduce reliance on trial-and-error methods, and minimize both time and cost in experimental work. This study addresses this gap by systematically investigating the effects of nanomaterial incorporation on the mechanical and index properties of clayey soils, with prior literature organized chronologically and classified by soil type.
Nanotechnology, first conceptualized in 1959 and formally termed in the 1970s, involves the manipulation of materials at the atomic and molecular scale [12]. The National Nanotechnology Initiative (NNI) defines it as the control and transformation of matter at the nanometer level to achieve innovative applications across diverse scientific fields, including geotechnics. Over the past decade, significant attention has been given to treating soft soils, which typically exhibit high liquid limits and low bearing capacity, using nanomaterials to enhance their geotechnical properties.
Nanomaterials, such as Nano-clay, Nano-silica, Nano-copper, and Nano-Aluminum, possess high surface-to-volume ratios, unique particle shapes, and cation exchange capacities, enabling them to interact effectively with soil particles. This interaction reduces void ratios and improves soil strength through intermolecular overlap. Studies have demonstrated their potential to significantly enhance soil stability, permeability, compaction, and shear strength, even at low dosages (<1% of dry soil weight). Research in [12], [13], and [14] has explored the mechanisms, advantages, and chemical stabilization effects of nanoparticles, while highlighting the distinct properties of nano-scale particles (1–100 nm) compared to conventional clay (0.1–2 mm). Applications extend to embankment stability and other geotechnical structures. Despite promising findings, the field still lacks comprehensive guidelines on optimal nanoparticle selection and dosage tailored to specific soil types—an area this study seeks to address to improve efficiency, reproducibility, and sustainability in soil improvement practices.

2. Characteristics of Soft Soil with Nanomaterials

Soft soils, typically characterized by high water content, low shear strength, and high compressibility, pose considerable challenges to geotechnical engineering applications. These soils often exhibit settlement potential approaching the liquid limit, making them unsuitable for direct construction without prior improvement. The integration of nanomaterials into soft soils has emerged as an effective approach to enhance their mechanical and physical characteristics, with improvements varying according to both soil type and nanomaterial content.

- Clayey soft soils

Clay-rich soft soils generally present high plasticity and low bearing capacity. Studies have shown that the inclusion of nanomaterials such as nano-silica, nano-clay, and nano-alumina significantly improves unconfined compressive strength (UCS) and reduces plasticity index (PI). The mechanical improvements observed with Nano-silica addition (0.5–2% by dry soil weight) have been reported to enhance UCS by up to 60%, attributed to the formation of additional cementitious bonds between particles and reduction in void ratio. Nano-clay particles fill micro- and nano-scale voids, leading to higher compaction density and improved stiffness. Physical improvements are observed through a reduction in PI and an increase in optimum moisture content are commonly observed alongside improved durability under wetting-drying cycles [15 – 19].

- Organic soft soils

Organic-rich soils, often found in coastal and deltaic regions, exhibit low strength and high compressibility due to high organic matter content. The application of nano-calcium carbonate and nano-silica has been effective in promoting particle aggregation and reducing compressibility. The mechanical improvements could be seen as: UCS improvement of 40–50% has been achieved with nano-Calcium carbonate ($CaCO_3$) dosages of 1–1.5%, owing to enhanced particle bonding and partial replacement of weaker organic matrices. Physical improvements are observed as permeability decreases significantly, contributing to better stability under saturated conditions [20 – 25].

- Peaty soft soils

Peat soils are extremely compressible and acidic in nature, making stabilization particularly challenging. Nano-silica and Nano-magnesium oxide have shown promise in increasing bearing capacity by accelerating pozzolanic reactions when combined with conventional stabilizers like lime or cement. The mechanical improvements could be seen through up to a 35% increase in UCS at low nanomaterial dosages (<1%) due to microstructural densification. The physical improvements are observed as a notable reduction in void ratio and moisture susceptibility, with improved resistance to long-term deformation [26].

- Marine soft clays

Marine clays, characterized by high salinity and low permeability, have been treated with nano-silica and nano-alumina to mitigate settlement and improve load-bearing performance. The mechanical improvements observed with Nano-silica content of 1–2% can double the initial stiffness modulus, improve load transfer, and reduce primary consolidation settlement. Physical improvements are observed as shrink–swell potential decreases markedly, while moisture retention is optimized for enhanced stability [27].

Across different soft soil types, nanomaterial content plays a critical role in determining improvement efficiency. Optimal dosages typically range from 0.5% to 2% by dry soil weight, beyond which improvements plateau or may even decline due to particle agglomeration and reduced reactivity. Lower dosages are often more cost-effective and environmentally sustainable, while still yielding substantial gains in strength, stiffness, and durability. These observations are listed in the comparative Table 1. Specific observations for Clayey soft soil reveal that for nano-SiO_2, the optimal dosage is around 0.5–1.0%. Too high (>2%) risks particle agglomeration and reduced effectiveness. For nano-Clay, the improvements are modest but consistent. Gains flatten after ~1.5–2%. For nano-MgO, data show strong early strength improvements at ~1.0%, but higher dosages may disturb soil structure.

Table 1: Summary of soft soil characteristics and improvements with nanomaterial incorporation

Soft soil type	Nanomaterial used	Optimal dosage	Mechanical improvements	Physical improvements
Clayey soft soils	Nano-SiO_2	0.25%	↑ UCS by ~10–15%; early strength gains due to pozzolanic activity	↓ LL & PI slightly; ↑ dry density
		0.5%	↑ UCS by 25–30%; improved bonding between clay particles	↓ PI by ~10%; ↑ compaction
		1.0%	↑ UCS by 50–60%; peak improvement at low dosages	Significant ↓ PI (20–25%); ↑ durability
	Nano-clay	0.5%	↑ UCS ~15%; minor stiffening effect	Slight ↑ compaction, ↓ LL
		1.0%	↑ UCS 25–30%; enhanced cohesion	↓ PI ~12%; ↑ dry density
		2.0%	Strength plateau, minor gain beyond 1%	↓ plasticity further, but the risk of brittleness
	Nano-MgO	0.5%	↑ UCS by 20–25%; initiation of hydration products	Slight ↓ void ratio; ↑ density
		1.0%	↑ UCS 40–50%; improved stiffness & resistance to deformation	↓ PI by ~15%; ↑ durability under wetting–drying
		2.0%	UCS begins to decline (soil disturbance effect)	Marginal ↓ PI, micro-cracking observed
Organic soft soils	Nano-$CaCO_3$, Nano-SiO_2	1.0%–1.5%	↑ UCS by 40–50%, improved bonding in the organic matrix	↓ Permeability, ↑ stability under saturation
Peaty soft soils	Nano-SiO_2, Nano-MgO	<1.0%	↑ UCS up to 35%, accelerated pozzolanic reactions (with lime/cement)	↓ Void ratio, ↓ moisture susceptibility, ↑ deformation resistance
Marine soft clays	Nano-SiO_2, Nano-Al_2O_3	1.0%–2.0%	↑ Stiffness modulus by 100%, ↓ settlement	↓ Shrink–swell potential, optimized moisture retention

'↑' denotes increasing, and '↓' denotes decreasing.

3. Behavioral Analysis of Soft Soils Stabilized with Nanomaterials

3.1 Physical behavioural analysis

The properties described in this section are determined as an average value of all nano types at each percentage of nano. Figures 2, 3, and 4 present the average values of plasticity indices, liquid limit (LL), plastic limit (PL), and PI at each nano percentage. The behaviour exhibited dramatic variation around the low percentages of less than 1%. The LL and PL tend to show a prominent increase with the minimal increase in nano percentage up to 0.4% followed by an aggressive drop at 0.5% and 0.7% nano percentages. The indices then steadily increased beyond the 1% nano content up to reaching above 60% and 30% for LL and PL, respectively. These results are like those observed in recent studies for high nano content [28]. In case of PI, the same behaviour is identified, however, with more ups and downs by a range of 1.5% of PI within the range of nano content 0.05% to 1%. This fluctuation in PI value is highlighted within a low nano percentage of nano clay and Magnesium oxide (MgO) [29, 30].

Besides, the regression relation between the PI and the nano content shows a significant R2 value. Meanwhile, the dry density value tends to present a decreasing value with respect to the increase of nano content Fig. 5. The behavior exhibited an aggressive decrement rate during the range of 0.05% to 0.3% to value less than 17.4 kN/m3 followed by improvement in clayey soil density up to 17.65 kN/m3 at nano content 0.35%. The decrement trend then tends to be more constant at a higher content ratio, indicating a good-powered correlation with an R2 value equal to 0.87. This attitude is justified by previous works due to the disturbance of the soil structure by excessive nano content [29, 31] as observed by SEM analysis of [32].

3.2 Mechanical behavioural analysis

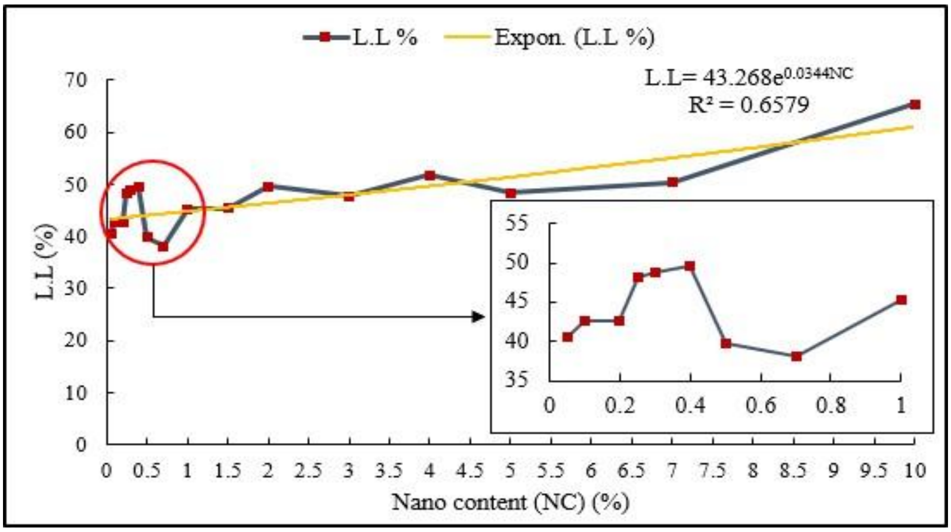
Fig. 6-a presents the behaviour of average peak stress ($\boldsymbol{\sigma}$) (i.e., peak compressive stress) with respect to the nano content added to clayey soil. The peak stress rapidly increased by increasing the nano content, reaching the optimal value at 0.4 % of nano. Then followed by a gradual decrement up to a nano percentage of 1 % while the compressive strength behaviour was observed to more constantly decrease behind this point. Other research approved this optimal value in terms of compressive stress, such as [33] using nano silica and [34] in a review study. The ranges of peak compressive stress values presented in Fig. 6-b may provide good guidance for researchers in choosing a suitable range of nano values to improve compressive stress behaviour.

The regression analysis of nano content–strength relationship in Fig. 6a, shows that the relationship between nano content (NC) and peak stress (σ) was modelled using an exponential regression function, expressed as [σ=240.01e−0.219NC], yielding an R^2 value of 0.6393. This indicates that approximately 64% of the observed variability in peak stress can be explained by the fitted curve, reflecting a moderate level of statistical reliability. The regression captures the overall decreasing trend of peak stress with increasing NC. However, it does not adequately represent the non-linear behaviour evident in the experimental data, where strength initially increases within the range of 0.2–0.4% NC before declining at higher dosages. This discrepancy highlights a key limitation of employing a single exponential model, which may oversimplify the actual soil response and overlook dosage-dependent enhancement thresholds. Another limitation arises when datasets from different studies are averaged or pooled together. Such aggregation assumes homogeneous soil nanomaterial interactions, potentially obscuring context-specific variations linked to soil mineralogy, compaction state, or nanoparticle type. For instance, clayey soils may exhibit peak strength improvements at lower dosages compared to silty or sandy soils, while differences in testing protocols can further influence observed trends. From a practical perspective, while regression analyses are valuable for illustrating broad trends and establishing indicative relationships, they should not be regarded as precise predictive tools. To more accurately capture the optimum dosage and material-specific effects, piecewise regression, polynomial fitting, or machine learning approaches may provide greater fidelity. Furthermore, the transferability of laboratory-based models to field conditions remains constrained by factors such as nanoparticle aggregation, groundwater interactions, and soil heterogeneity, all of which warrant further investigation.

Fig. 7 and Fig. 8 present the behaviour of average cohesion (C) and internal friction angle (ϕ) with respect to the nano content of clayey soils. The average C values show that the optimum value is around 1.5 % of all types of nano content, indicating an inverse V-shape range between 0.5 % and 3 %. Meanwhile, for friction angle average value exhibited a more stable behaviour starting from 0.5 % up to 2 % nano content. Followed by an increment up to 32 at 3 % nano content compared to 23 ϕ value at 2 % nano content. It's important to highlight that the amount of data for demonstrating the behaviour of C and ϕ is much lower. This behaviour is well represented by polynomial second order equation for cohesion and internal friction.

The CBR average value of clayey soils incorporating many types of nano content is shown in Fig. 9. The demeanour of CBR average value is quite like the peak compressive stress showing an increasing trend attaining the optimal value at nano content of 0.35 % and 0.4 % then reflecting an enhancement in the bearing characteristics of clayey soil following the nano content increment. While the values tend to drop behind these values. This optimal value is close to that stated in [35] using nano bentonite. On the other hand, the drop of CBR behind the optimal values is observed in [36] due to increasing the compressibility, hence the saturation against bearing loads [39] or the decrease of density [37].

However, the current analysis in this section does not provide precise information on the optimum percentage of nano content for each mechanical or physical enhancement. It depends on the nano type rather than the nano content.



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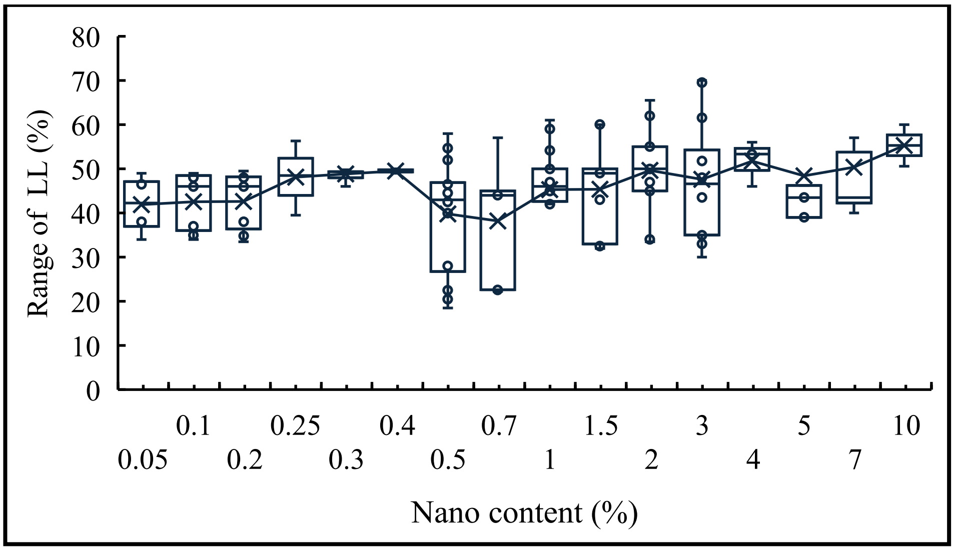
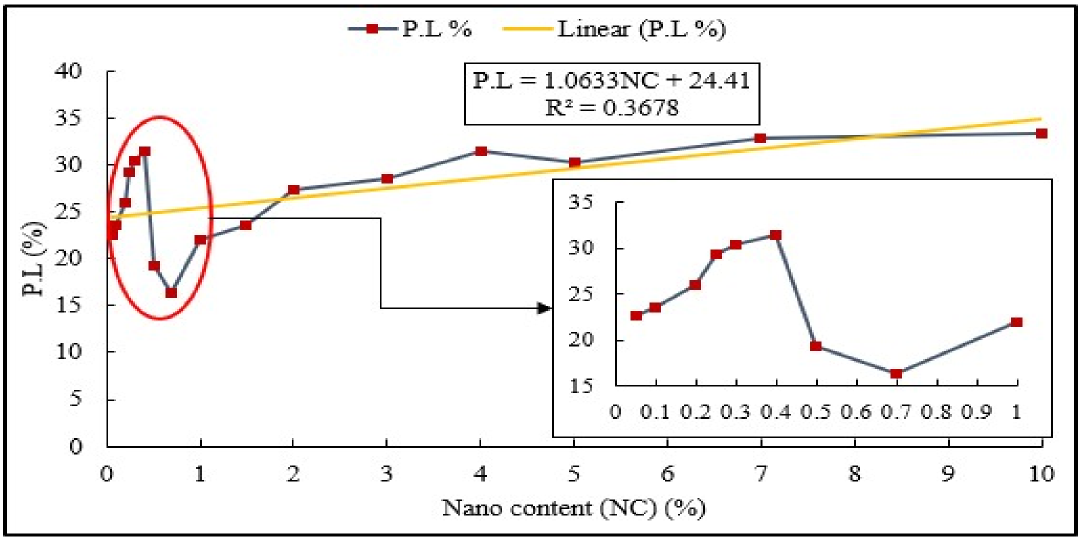


(b)

Fig. 2: a) Behaviour of average LL values and corelation, and b) Range of LL values at each nanomaterial content.



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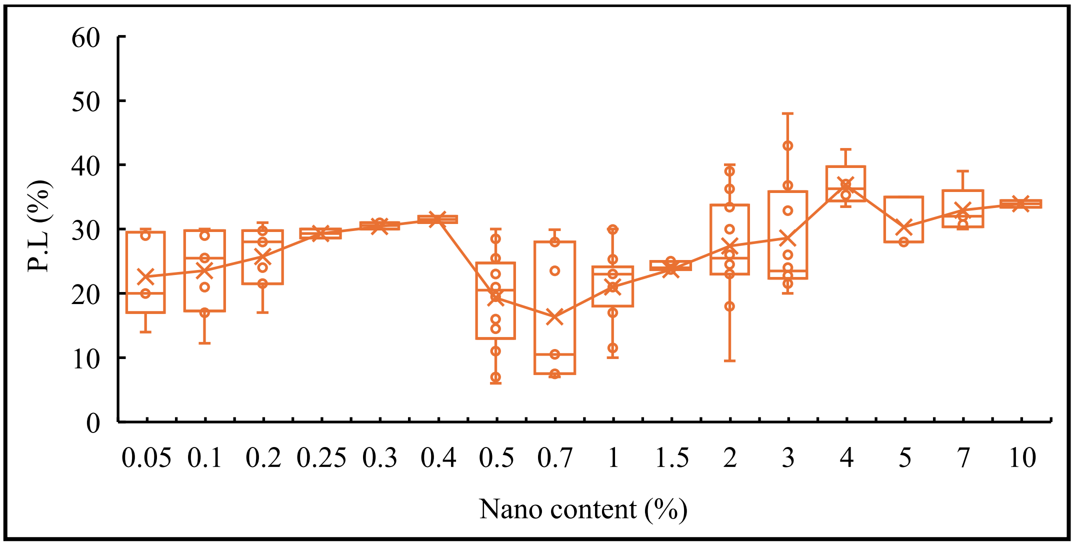

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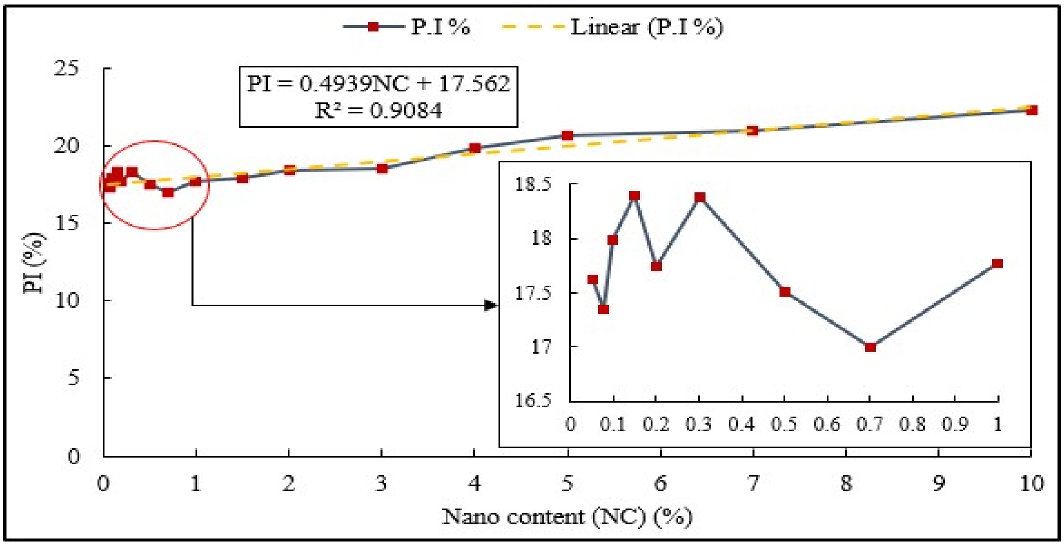
Fig. 3: a) Behaviour of average PL values and corelation, and b) Range of PL values at each nanomaterial content.



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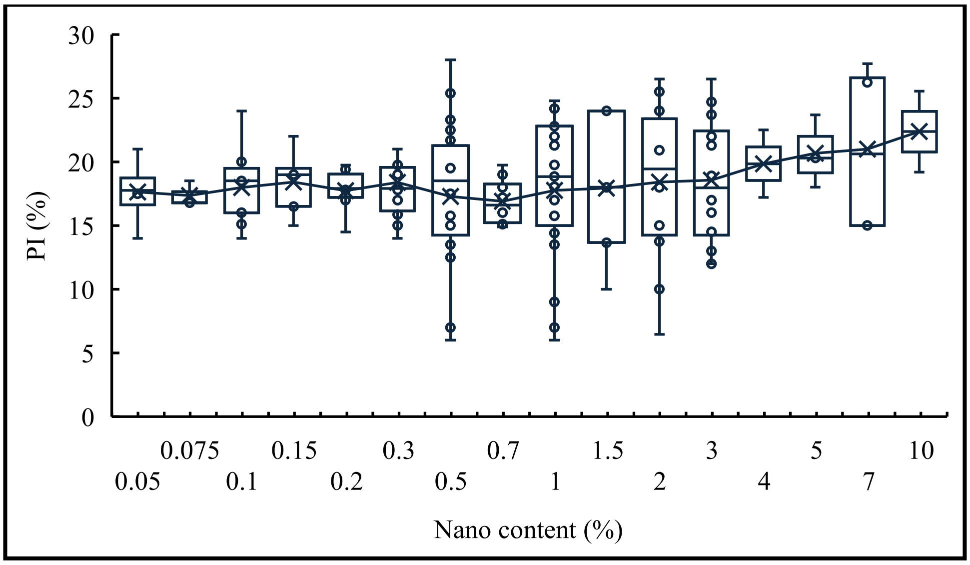
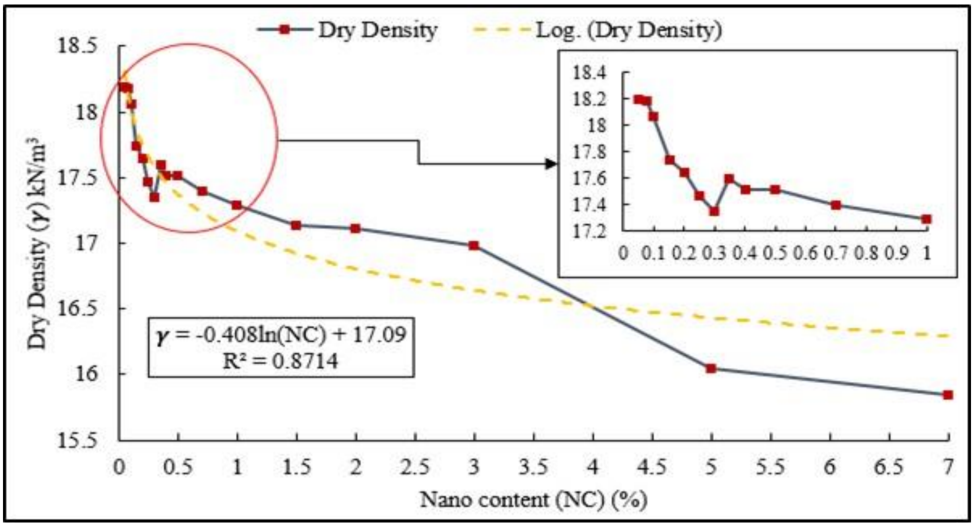


(b)

Fig. 4: a) Behaviour of average PI values and corelation, and b) Range of PI values at each nanomaterial content.



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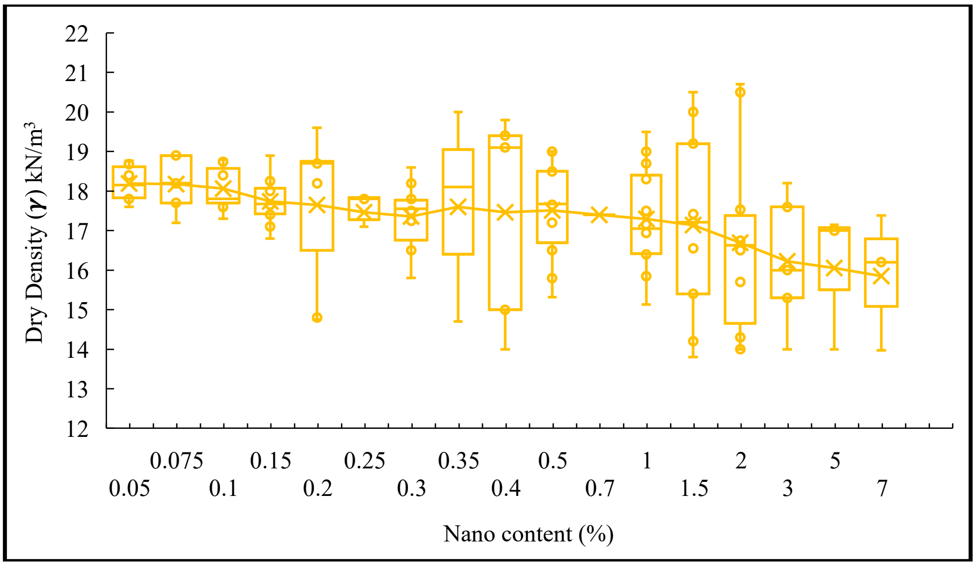
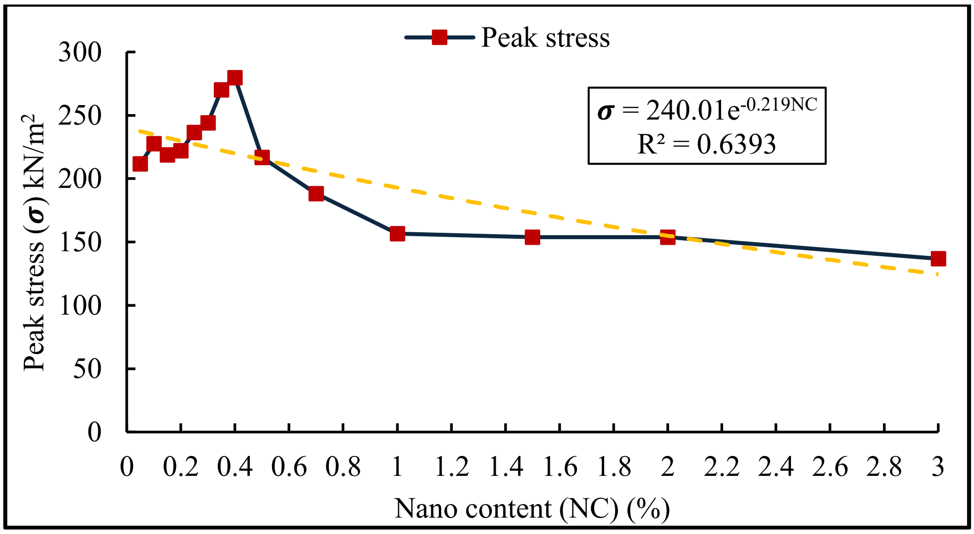


(b)

Fig. 5: a) Behaviour of average γ values and corelation, and b) Range of γ values at each nanomaterial content.



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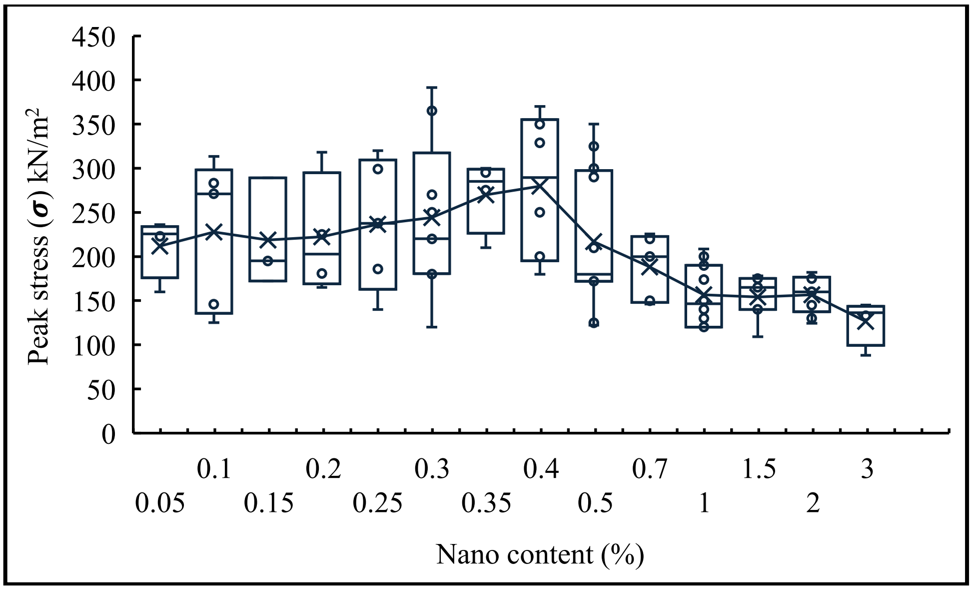

(b)

Fig. 6: a) Behaviour of average σ values and corelation, and b) Range of σ values at each nanomaterial content.

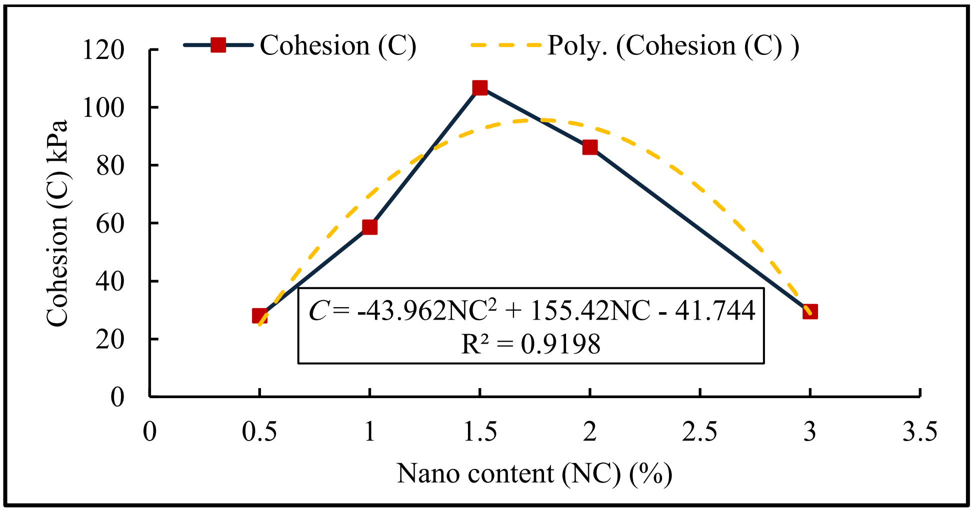

Fig. 7: Behaviour of average C values and corelation with respect to nanomaterial content.

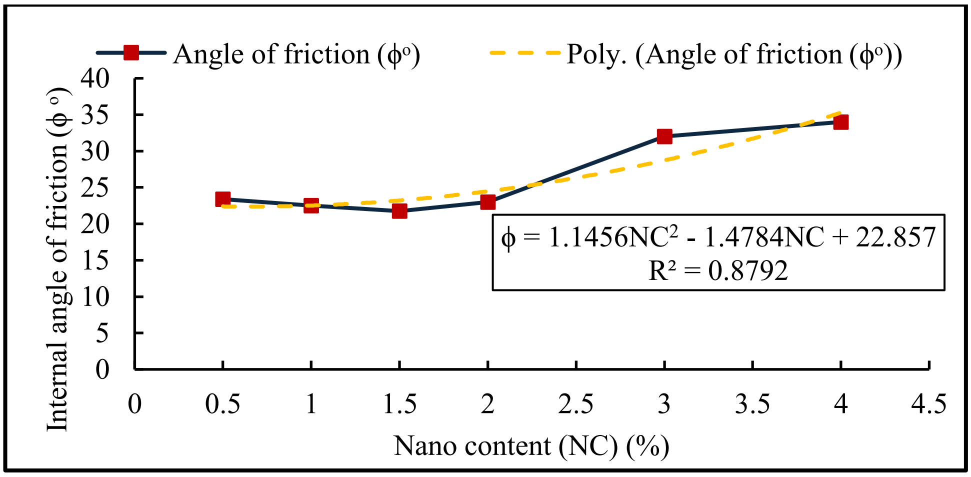

Fig. 8: Behaviour of average ϕ values and corelation with respect to nanomaterial content.

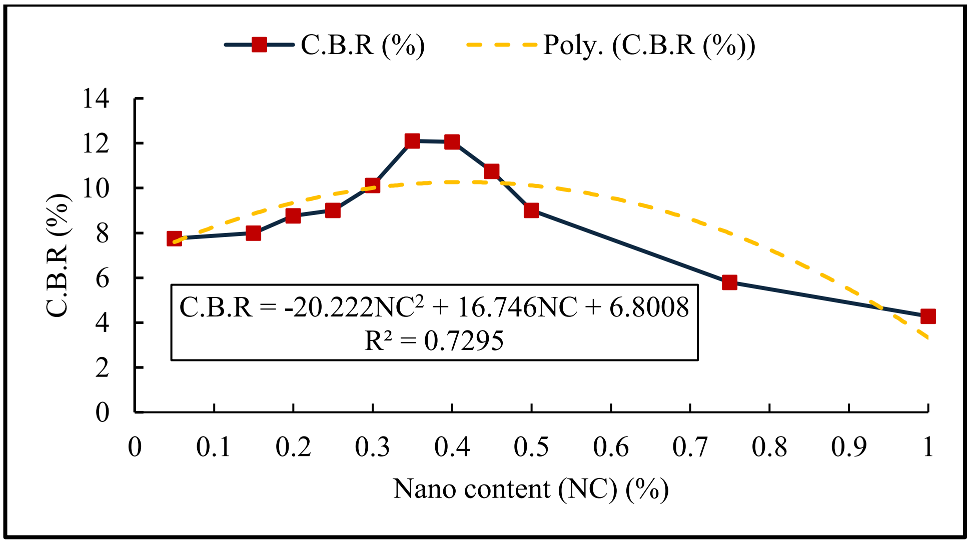

Fig. 9: Behaviour of average CBR values and correlation with respect to nanomaterial content.

4. Assessment and Discussion

4.1 Optimum nanomaterial percentage

In this section, the optimum nanomaterial percentage for each nanomaterial type corresponding to the physical and mechanical characteristics is assessed and discussed. Table 2 presents the optimum nanomaterial percentage by weight that provides the highest positive impact on the physical properties. These percentages are identified considering the enhancement in clayey soil characteristics. By means of the nanomaterial percentage provides a lower PI value, lower moisture content (MC), and higher density compared to the other percentages used in each research article. This analysis is limited to the range of nanomaterial percentages used in the study (i.e., the optimum percentage selected as the optimum compared to the other percentages used in that study).

In terms of PI, it's observed that the optimal percentage of nanomaterial content ranges between 0.15 % and 7 % which achieves a lower PI value considering the type of nano. Where the higher PI index value refers to higher compressibility of clayey soil [38, 39]. Meanwhile, the optimal percentages of nanomaterial to reach the lower MC are limited between 0.075 % to 7 % corresponding to the nanomaterial type. Considering that the lower value of MC reflects a higher density and void ratio [40]. On the other hand, the higher dry density is observed at a range of nanomaterial percentages of 0.075 % to 2 % based on the nanomaterial content. As the density of clayey soil increases lead to improvement in soil structure that contributes to the enhancement of stability and other mechanical characteristics [41]. Unlike the PI index optimal nanomaterial content, the MC and the dry density show a great compatibility in terms of percentage ranges. These results are justified by the direct proportionality relation between MC and the maximum dry density of soil. Table 3 shows that the optimum nanomaterial percentage or content achieves the better mechanical characteristics, particularly peak compressive stress (σ), cohesion (C), internal friction angle (ϕ), and CBR. For the peak compressive stress, the data collected is based on the results of an unconfined compressive test to avoid the variable contribution of confining pressure and type of confined test on the resulting peak stress. The range of nanomaterial percentage to achieve higher compressive stress is enclosed between 0.25 % and 7 % at various nano types. Meanwhile, the nano percentage reaches higher C and ϕ values are presented for Nano clay. For CBR, the higher value is observed at a nano percentage range of 0.25 % to 1 % for different nano types.

Based on the results from Table 2 and Table 3, the range of optimal nanomaterial percentage extensively depends on the examined property of clayey soil. However, in terms of nanomaterial type, it is observed that some nanomaterials have a more effective impact on specific physical and mechanical properties. In physical properties, the nano-Silica and nano-Bentonite are more effective in reducing the soil compressibility, NanoSiO2 and nano-clay are impactful for decreasing the MC, NanoSiO2 and Nano-Al_2O_3 are widely improving the dry density of clayey soil. For mechanical properties, the NanoSiO2 and Nano-TiO_2 contribute more to the compressive strength of clayey soil. Nano-clay, Nano-Bentonite, and NanoSiO2 effectively increase the shear strength parameters.

Table 2: The Optimum physical properties of clayey soil with respect to nano type and percentage.

Nano type	P.I	O.M.C	Dry Density (γ)	References
Nano-MgO	2-4%	2%	2%	[4]
Nano-SiO_2 fume	5%	1%	1%	[15]
Nano-TiO_2	1.5%	2%	2%	[44]
Nano-Fly-ash	1%	0.5%	0.5%	[15], [44]
NanoSiO_2	0.5 – 1%	7%	0.25%	[23], [37], [45], [46]
Nano-clay	0.5%	0.5%	0.15-0.5%	[42], [43], [47], [48]
Nano-Al_2O_3	0.15-0.3% or 1.5%	0.075-0.3% or 1.5%	0.075-0.1% or 1.5%	[36], [50]
Nano-Bentonite	7%	-	-	[51]
NanoZeolite	3-7%	-	-	[52], [53]
Nano-CuO	0.3-0.7%	0.15-0.5%	0.15-0.5%	[54]

Table 3: The Optimum mechanical properties of clayey soil with respect to nano type and percentage.

Nano type	Peak stress (σ)	C	Phi (ϕ)	C.B.R	References
Nano-MgO	0.3%	1-1.5%	0.5%	0.5-1%	[4]
Nano-SiO_2 fume	4%	1.5%	0.5%	0.7-1%	[15]
Nano-SiO_2	0.3-1.5% or 3%	2%	0.5-1%	0.7-0.75	[23], [37], [45], [46]
Nano-Fly-ash	-	2-4%	0.5%	1%	[44]
Nano-clay	0.25-0.4 or 1-2	2-4%	0.5%	0.25-1%	[42], [43], [47], [48]
NanoTerra-Sil	1.2%	2%	1%	1-1.5%-	[49]
Nano-Al_2O_3	1.5%	2%	1%	1-1.5%	[36], [50]
NanoBentonite	7%	1.5-2%	0.5-1%	1-1.5%	[51]
NanoZeolite	7%	1-2%	0.5%	0.5%	[52], [53]
Nano-CuO	0.7%	1-1.5%	0.5-1%	1%	[54]

4.2 Environmental and health impacts

While nanomaterials demonstrate promising potential in enhancing the engineering properties of soft soils, their environmental and health implications require careful consideration. Recent studies have highlighted that nanoparticles—owing to their ultra-small size (1–100 nm), large surface area, and high reactivity—can exhibit enhanced mobility within soil and groundwater systems. For instance, nano-silica and Nano-TiO_2 have been observed to migrate through porous media under certain geochemical conditions, potentially reaching aquifers and influencing water quality. The persistence of these particles in the subsurface environment raises concerns about their long-term fate and ecological impact.

Toxicological research indicates that certain nanoparticles, particularly metal oxides, can induce oxidative stress and cytotoxic effects in microorganisms, plants, and even higher organisms. These effects vary significantly depending on particle size, surface functionalization, aggregation state, and environmental conditions. Furthermore, nanoparticle soil interactions may be an alternative to microbial communities, influencing nutrient cycling and soil health. Despite these emerging findings, the understanding of chronic exposure impacts, bioaccumulation pathways, and potential risks to human health remains incomplete, necessitating further multidisciplinary investigation.

From a regulatory perspective, there are currently no universally adopted standards or guidelines specifically addressing the use of engineered nanomaterials in geotechnical engineering. Existing frameworks, such as the ISO Technical Committee 229 on nanotechnologies, OECD Working Party on Manufactured Nanomaterials (WPMN), and national occupational safety guidelines, provide general recommendations on nanomaterial handling, exposure limits, and environmental release, but these are not tailored to subsurface engineering contexts. The absence of application-specific standards for soil stabilization projects means that practitioners must rely on laboratory safety protocols and extrapolated environmental risk assessments, which may not adequately reflect field-scale conditions.

Given the increasing adoption of nanomaterial-based soil improvement methods, there is a clear need for the development of evidence-based policies and technical guidelines. Such frameworks should address permissible nanoparticle concentrations, environmental monitoring requirements, lifecycle assessments, and safe disposal or remediation strategies. Collaboration between geotechnical engineers, environmental scientists, toxicologists, and regulatory bodies will be essential to balance the benefits of nanotechnology with responsible stewardship of environmental and public health.

To limit nanoparticle risks in soil stabilization, three main approaches are recommended:

- Material design: Use functionalized or matrix-bound nanoparticles to reduce mobility and apply the lowest effective dosage.
- Construction practices: Employ wet mixing, dust suppression, proper PPE, and containment barriers to minimize release during handling.
- Monitoring and lifecycle management: Track nanoparticle migration with groundwater and soil monitoring, assess ecological effects, and integrate life-cycle assessments (LCA) to guide safe use and disposal.

Existing standards (e.g., ISO TC-229, OECD WPMN) provide general nano-safety guidance but not subsurface-specific rules. Tailored frameworks should set permissible concentrations, monitoring requirements, and end-of-life protocols. Incorporating findings from Chemosphere and Environmental Science & Technology into geotechnical guidelines will ensure that soil performance gains are achieved alongside environmental and health protection.

5. Conclusion

This work consolidates current knowledge on the use of nanomaterials for improving the properties of clayey soils, providing critical insights into their optimal application. The analysis highlights those small quantities of nanomaterials, often less than 1% by weight, can lead to substantial enhancements in soil strength, density, and stability. Variations in optimal nanomaterial content, typically ranging from 0.25% to 7% depending on the type and target property, underscore the need for precise calibration in geotechnical projects. NanoSiO2, Nano-clay, and Nano-TiO2 have emerged as effective agents for reducing plasticity and increasing compressive strength, while combinations with lime or other stabilizers further improve outcomes. Furthermore, the study identifies the critical role of nanomaterials in achieving sustainable soil stabilization solutions. By improving soil characteristics with minimal environmental disruption, nanomaterials offer a promising alternative to traditional chemical stabilizers. However, challenges remain in the form of cost considerations, potential environmental impacts of nanoparticle usage, and the lack of standardization in testing and implementation protocols. Addressing these gaps

through collaborative research and the development of standardized frameworks can significantly enhance the practical application of nanotechnology in geotechnics. The review also underscores the importance of long-term monitoring to assess the durability and effectiveness of nanomaterial-enhanced soils under varying environmental conditions. Future investigations should focus on the integration of nanomaterials with other innovative stabilization techniques and the exploration of their multifunctional benefits, such as their potential to mitigate soil contamination or improve water retention. By optimizing nanomaterial content and expanding the scope of their applications, this study provides a roadmap for sustainable and efficient soil stabilization techniques, supporting advancements in construction, infrastructure development, and environmental management.
Additionally, while nanomaterials demonstrate significant potential for enhancing soft soil properties, their environmental and health implications require careful consideration. Recent studies indicate concerns over nanoparticle mobility, persistence, and potential toxicity to soil biota and humans. The absence of geotechnical-specific standards highlights the urgent need for clear guidelines on safe use, environmental monitoring, and disposal. Importantly, long-term monitoring of nanomaterial-stabilized soils under real environmental conditions is essential, as laboratory results may not fully reflect field performance. Future policy development should balance the technological benefits with robust safeguards for environmental and public health protection.

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