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TECHNICAL NOTES

Nanomaterials in Geotechnical Engineering: A Comprehensive Review on Soil Improvement Techniques

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ABSTRACT

In response to the rapid evolution of nanotechnology and the interdisciplinary integration of emerging technologies, the use of nanomaterials in geotechnical engineering, with a particular focus on soil improvement, has gained considerable attention. This study provides a comprehensive examination of the application of nanoparticles in soil stabilization and explores the ensuing implications. The review delves into the potential benefits offered by nanotechnology, presenting innovative solutions within the realm of soil improvement. The analysis encompasses a thorough review of studies employing nanomaterials in geotechnical and geological engineering, elucidating the intricate ways in which these nanoparticles contribute to enhancing soil properties. Furthermore, the paper investigates the underlying mechanisms governing nanomaterials in soil improvement, shedding light on their synergies with traditional stabilizers and emphasizing the advantages they offer over conventional materials, waste products, and fibers. By synthesizing current research, this paper not only showcases promising methodologies that employ nanomaterials for soil improvement but also advances our understanding of the dynamic interplay between nanotechnology and geotechnical engineering. This contributes to the development of innovative approaches for sustainable advancements in the field, paving the way for future research and application.

Keywords: Nanomaterials; Geotechnical Engineering; Soil improvement; Stabilization; Sustainable Advancements

1. Introduction

Soil improvement is an indispensable facet of civil engineering, playing a pivotal role in ensuring the stability and longevity of structures across diverse terrains on Earth (Alhamdi and Albusoda, 2021; Asgari et al., 2015; Bayat et al., 2023; Hakimelahi et al., 2023). The significance of soil improvement becomes evident in its capacity to enhance crucial engineering properties, addressing challenges such as low bearing capacity, settlement issues, and inadequate shear strength (Ghasem Ghanbari et al., 2022; Nicholson, 2014; Saleh et al., 2019). One primary motivation for soil improvement is the mitigation of risks associated with foundation failure and uneven settlement, thereby safeguarding the structural integrity of buildings, bridges, and various infrastructural elements. Extensively utilized across various contexts such as road construction, embankments, and erosion-vulnerable zones, the strategic implementation of soil stabilization techniques and materials not only guarantees the durability and robustness of infrastructure but also plays a pivotal role in promoting sustainable construction practices by reducing environmental impact (Daud et al., 2019; Feng et al., 2024b; Ghanbari and Bayat, 2022).

As illustrated in Figure 1, various methods are employed to achieve soil improvement, showcasing a spectrum ranging from traditional techniques like compaction and preloading to modern advancements such as chemical stabilization, grouting, and geosynthetics (Nicholson, 2014). Each method is meticulously tailored to the specific soil conditions and project requirements, exemplifying the versatility inherent in soil improvement as a fundamental practice in civil engineering. Chemical stabilization, biological stabilization, and mechanical stabilization emerge as three distinct approaches to enhancing soil properties (Mousavi and Wong, 2016). Chemical stabilization, utilizing additives both traditional and nontraditional, involves introducing certain chemicals such as lime, cement, or other stabilizing agents into the soil to alter its physical and chemical characteristics (Yabaluie Khamesluei et al., 2024). These chemicals react with soil particles, enhancing cohesion, reducing swelling, and increasing load-bearing capacity. The focus of the present study is on soil stabilization using nanomaterials, with various types of nanoparticles being employed either independently or in conjunction with other materials.

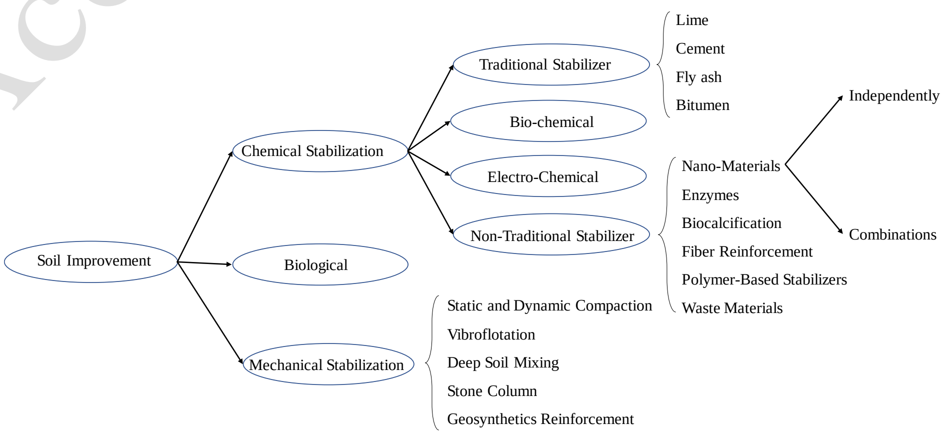

Figure 1. General soil stabilization methods

Innovative techniques within the realm of chemical stabilization include bio-chemical stabilization and electro-chemical stabilization, each leveraging unique mechanisms to enhance soil properties (Ayodele et al., 2017). Bio-chemical stabilization integrates biological and chemical elements by employing compounds derived from living organisms, such as enzymes or polymers, to interact with the soil (Arabani and Shalchian, 2023; Feng et al., 2024a). This approach aims to modify the soil's structure, improve water retention, and reduce erosion. For instance, Microbially Induced Calcium Carbonate (MICP) involves bacteria inducing the formation of calcium carbonate to bind soil particles (Bayat et al., 2021). In contrast, electro-chemical stabilization involves manipulating the electrical properties of the soil through the application of electrical currents, capable of altering the soil's pH, mineral content, and overall stability (Ayodele et al., 2017; Kollannur and Arnepalli, 2021). Bio-chemical and electro-chemical stabilization represents a progressive shift in soil improvement practices, providing distinctive solutions for targeted engineering challenges and contributing to sustainable construction methods. While electro-chemical stabilization relies on electrical processes, biological stabilization takes a divergent approach by leveraging living organisms or their byproducts to reinforce the soil. Methods like MICP, where bacteria generate calcium carbonate to bind soil particles, along with the utilization of plant roots and mycorrhizal fungi, actively enhance soil structure and stability. This holistic integration of biological elements showcases a promising avenue for eco-friendly and innovative approaches to soil improvement (Arabani and Shalchian, 2023).

Finally, mechanical stabilization relies on altering the physical properties of the soil through techniques like compaction, vibro-flotation, or the introduction of reinforcing elements such as geosynthetics (Anbarani et al., 2023). Each approach, with its unique advantages, is chosen based on specific soil conditions, project requirements, and environmental considerations, underscoring the versatile nature required in soil improvement practices within the field of civil engineering (Das, 2003).

The burgeoning field of soil stabilization using nanomaterials heralds a paradigm shift in civil engineering practices, introducing innovative approaches to address longstanding challenges. The integration of nanotechnology into soil improvement techniques presents a novel frontier, allowing for precise manipulation of soil properties at the nanoscale (Kumar and Devi, 2023). This review paper will delve into the latest advancements, exploring various types of nanoparticles and their applications in civil engineering, with a specific focus on soil stabilization. From enhancing strength and durability to mitigating environmental impact, incorporating nanomaterials showcases the potential for sustainable and highly effective solutions, marking a transformative era in the quest for resilient and eco-friendly construction practices.

2. Nanomaterials

The concept of nanotechnology was originally introduced by Richard Feynman in 1959 during his lecture titled "There's Plenty of Room at the Bottom" (R. Feynman, 1960), marking the inception of a revolutionary scientific and technological paradigm. Nanomaterials, a pivotal component of nanotechnology, are characterized by having at least one dimension ranging from 1 to 150 nanometers. It is noteworthy that the properties of nanomaterials often diverge significantly from those exhibited by the same materials at the micro (10^{-6} m) or macro-scale (10^{-6} to 10^{-3} m). Nanoscience, an extension of conventional sciences into the nanoscale, delves into the study of phenomena and the manipulation of materials at this remarkably small scale.

Nanomaterials exist in natural and artificial forms. Natural examples include proteins, lipids, and nucleic acids, while artificial nanomaterials are engineered for specific applications (Mukhopadhyay et al., 2018; Vajtai, 2013).

Their synthesis follows two main approaches: top-down and bottom-up (Figure 2) (Vajtai, 2013). The top-down method refines bulk materials into nanoscale structures using precision techniques. The bottom-up approach assembles nanoparticles from atomic or molecular building blocks, leveraging self-assembly to create complex architectures.

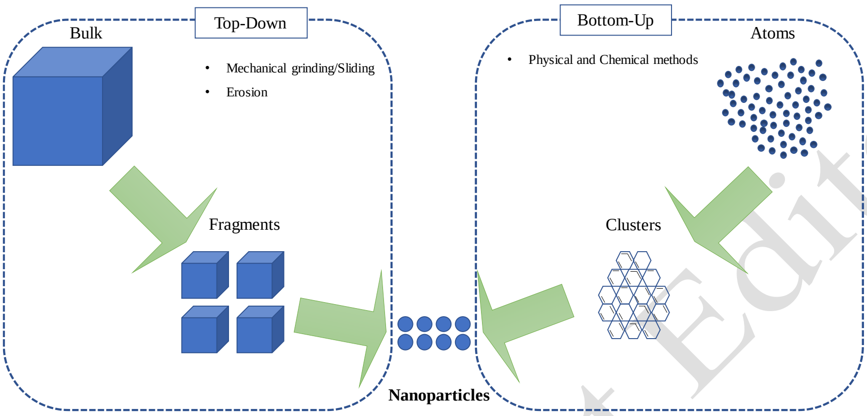

Figure 2. Top-down and bottom-up methods in nanomaterial synthesis.

The growing interest in nanomaterials has led to their widespread application, including soil stabilization. Understanding their synthesis methods is crucial for advancing civil engineering applications. For a detailed discussion of nanomaterial properties, see Vajtai (2013).

2.1. Morphology as a Governing Factor

The shape of nanomaterials plays a crucial role in determining their properties. Factors such as aspect ratio, porosity, and surface roughness affect the surface-to-volume ratio, influencing material behavior. Nanomaterials, typically 1–100 nm in size, are categorized into four types based on their dimensions as shown in Figure 3:

- 0-D nanomaterials (e.g., nanoparticles) have all dimensions in the nanoscale and exhibit isotropic properties.
- 1-D nanomaterials (e.g., nanotubes) have two nanoscale dimensions and one in the microscale, making them anisotropic.
- 2-D nanomaterials (e.g., nanoplates) feature nanoscale height with microscale length and width.
- 3-D nanomaterials have all three dimensions in the microscale, exceeding 100 nm.

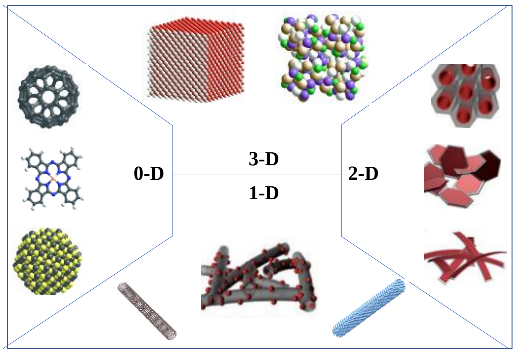

Figure 3. Top-down and bottom-up methods in nanomaterial synthesis.

2.2. Bonds and Structures at the Nanoscale

The compressive strain in bulk solids, usually limited due to strong bonds, takes on a transformative role at the nanoscale. Forces near surface atoms induce asymmetry, altering the bond lengths of nanomaterials. This effect becomes increasingly pivotal in clusters and nanoparticles, typically ranging from 1–5 nm, where the surface atom to volume atom ratio (dispersion) plays a decisive role (Vajtai, 2013).

2.3. Mechanical Strength and Defects

Nanomaterials exhibit distinct mechanical properties attributable to shorter bond lengths, resulting in stronger and stiffer materials. The limited size of material units reduces the probability of certain defects, such as rare grain boundaries in small nanoparticles. Materials like graphene and carbon nanotubes showcase high strength and Young's modulus due to their strong in-plane bonds (Vajtai, 2013; Wu et al., 2020).

2.4. Electromagnetic Behavior and Quantum Effects

Nanoscale materials, particularly those with dimensionality zero to two, unveil intriguing electromagnetic behavior influenced by quantum confinement. Changes in electrical properties, such as widening bandgaps and decreasing conductivity, accompany decreases in feature size. Optical properties also transform, introducing quasiparticles like excitons and playing a pivotal role in interactions with optical phonons.

2.5. Thermal Properties

Thermal conductivity, specific heat, melting point, and glass-transition temperature in nanomaterials are heavily contingent on particle or feature size. Phase diagrams are intricately linked to size, shape, and the environment, underscoring the complex interplay of thermal properties in the nanoscale realm (Vajtai, 2013).

2.6. Chemical Properties and Reactivity

Chemical approaches dominate nanomaterial preparation processes, with subsequent modifications often required for specific applications. Nanomaterials, ranging from fullerenes to metallic and ceramic variants, exhibit diverse reactions and products contingent on size and shape. Chemical transformations of nanoalloys represent a substantial domain in nanomaterial chemistry (Asha and Narain, 2020).

2.7. Nanomaterial Performance in Corrosive Environments

The historical utilization of nanomaterials in corrosion prevention, as seen in artifacts like Chinese heiqigu mirrors coated with SnO_2 nanoparticles, underscores the ongoing significance of nanomaterials in shielding against deterioration. Notable examples, such as the Mayan blue paint, which remains corrosion-resistant even after centuries of burial in soil, serve as compelling evidence of the enduring efficacy of nanomaterials in the preservation of artifacts (Vajtai, 2013).

This in-depth exploration establishes a foundation for a more profound comprehension of nanomaterial properties, paving the way for a subsequent emphasis on civil engineering, particularly in the context of soil stabilization with these intriguing materials.

3. Nanomaterials Advancement in Geotechnical Engineering: A Focus on Soil Improvement

In the realm of geotechnical engineering, the integration of nanomaterials marks a pioneering venture that holds significant promise (Ghasabkolaei et al., 2017). This burgeoning field explores the application of nanotechnology to address soil-related challenges and enhance the performance of geotechnical structures. Nanomaterials, such as nanoparticles and nanocomposites, are deployed to modify soil properties, improving factors like stability, strength, and permeability. These advancements aim to revolutionize traditional soil stabilization techniques, providing sustainable and efficient alternatives. As advancements in nano-geotechnics unfold, the growing influence of nanomaterials on elevating the geotechnical properties of geomaterials becomes more apparent. This evolution is actively shaping the future trajectory of geotechnical engineering practices (Firoozi et al., 2021).

Soil stabilization, a critical aspect of geotechnical engineering, undergoes a transformative evolution with the integration of nanomaterials (Ingles and Metcalf, 1972). The challenges posed by ground and structural reinforcement, coupled with the imperative of environmental sustainability, have led to a reevaluation of traditional soil improvement methods (Damians et al., 2023). Materials like cement and chemical grouts, while effective, face limitations in terms of full-field treatment, environmental impact, and cost (Shahidi et al., 2024; Verma et al., 2009). The urgency to address these challenges has prompted the exploration of novel materials, and nanotechnology has emerged as a game-changer in the realm of soil strength improvement (Huang et al., 2021).

A fundamental and distinctive attribute of nanomaterials is their minute size. When incorporating nanomaterials into other granular substances like soils, the critical consideration lies in the relative size of these particles to the nanomaterials. Soil is weakly accumulated mineral articles that range from as large as 75mm to as small as 1nm and because of that soil is one of the most complicated materials to study based on their particle sizes. Soil classification is a fundamental aspect of geotechnical engineering, categorizing soil into four primary types based on particle size: gravel, sand, silt, and clay (Das and Sivakugan, 2017). This classification is essential for understanding the soil's engineering properties and behavior. Additionally, soils are further distinguished based on their plastic properties, creating two main categories: cohesive and non-cohesive soils.

The Unified Soil Classification System (USCS) is a standardized method for classifying soils based on physical and engineering properties. It categorizes soils into gravel, sand, silt, and clay, aiding engineers in foundation design, site evaluation, and soil stabilization. Figure 4 illustrates this classification and highlights the size contrast between soil particles and nanoparticles. This comparison underscores the nanoscale dimensions of engineered or natural nanoparticles and their potential to modify soil properties at a microscopic level, enhancing soil stabilization techniques.

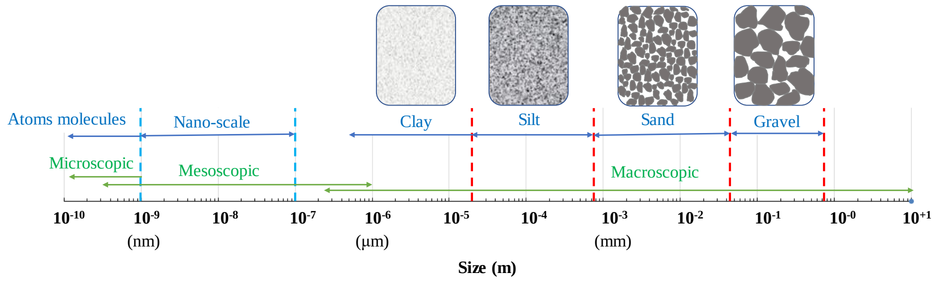

Figure 4. A comparative overview of soil particle sizes in relation to nanomaterial sizes

3.1. Review of nanomaterial applications in soil stabilization

In this comprehensive review study, a total of 96 papers published in various journals and conferences have been systematically analyzed. The extensive list of references underscores the substantial volume of research conducted in recent years on soil improvement using nanomaterials, highlighting the contemporary and compelling nature of this subject. These scholarly works investigate the utilization of nanomaterials for soil stabilization through three distinct approaches: standalone application, combination with other materials, and incorporation as injection materials, as illustrated in Figure 5. The quantitative breakdown of these studies reveals that nanomaterials have been employed independently in 33% of the cases, combined with other materials in 57% of instances, and used as injection materials in 10% of scenarios. This statistical distribution underscores the prevalent trend in research, indicating a significant preference for combining nanomaterials with other additives such as lime and cement rather than employing them as standalone agents or for injection purposes.

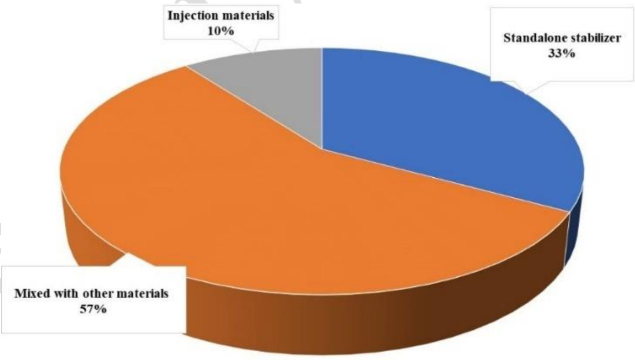

Figure 5. Comparative Analysis of Nanomaterial Applications in Soil Stabilization – Standalone, Mixed, and Injection Approaches in Reviewed Studies

In the standalone application of nanomaterials, a consistent methodology emerged in the reviewed studies. Generally, a predetermined weight of dry nanomaterials was incorporated into the soil, with careful mixing to achieve homogeneity. Following this, a specified water content, typically determined through the Proctor compaction test, was introduced, and thoroughly blended until uniform moisture distribution permeated the soil-nanomaterial mixture. This manual mixing process was executed with meticulous attention, investing sufficient time to guarantee homogeneity. The prepared samples were then subjected to a curing period, after which they were utilized for a battery of tests, including Unconfined Compressive Strength (UCS), California Bearing Ratio

(CBR), Direct Shear, Triaxial tests, or other tests. The experimental conditions were controlled, maintaining constant temperature and humidity during sample processing. Notably, the reviewed literature emphasized the critical importance of sample homogeneity, a consistent theme across articles. This meticulous attention to homogeneity underscores its significance in ensuring the reliability and reproducibility of test results in studies focused on soil stabilization using nanomaterials, whether applied in standalone form or in conjunction with other stabilizing agents and fibers. Additionally, variations were observed in the calculation methods for nanomaterial content, either based on the total weight of dry soil or as a replacement for other additives such as cement and lime, reflecting the diversity in experimental approaches within the body of literature.

Figure 6 depicts the utilization of nanomaterials in different soil types through standalone, mixed, and injection approaches within the reviewed studies. This comprehensive examination offers valuable insights into the diverse applications of nanomaterials across various soil types. As evident in Figure 6, nanomaterials employed in standalone and mixed methods primarily focus on enhancing clay soils. Conversely, in the injection approach, their predominant use is for improving sandy soils.

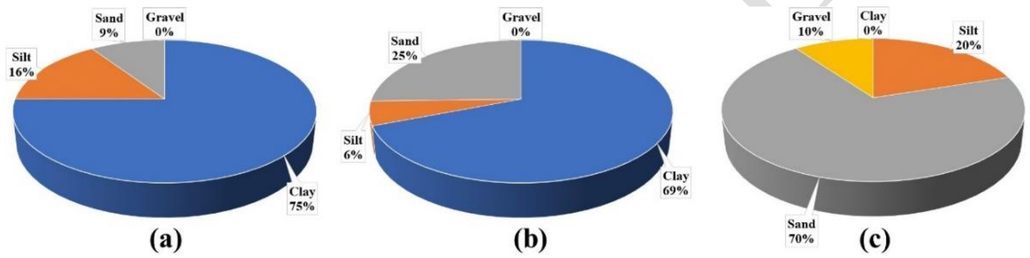

Figure 6. Schematic representation of nanomaterial applications in soil stabilization including (a) standalone approach, (b) mixed approach, and (c) injection approach

The stabilization of clay soils involves a multifaceted approach due to the unique engineering challenges posed by these cohesive and expansive materials. Clay soils are characterized by their fine particle size and high plasticity, resulting in properties such as low bearing capacity, high compressibility, and susceptibility to swelling and shrinkage (Aziz, 2023). To counteract these challenges and enhance the engineering properties of clay soils, various methods, and materials, including nanomaterials, have been employed. Nanomaterials, with their minuscule size and high surface area, offer the potential for improved soil-particle interaction and enhanced stabilization effects (Arora et al., 2019). Additionally, nanomaterials can modify the soil structure, increase cohesion, and reduce permeability.

A tailored approach is essential for improving the strength and stability of clay soils in construction and infrastructure. Nanomaterials offer an innovative strategy in this field. However, injection methods have primarily been applied to sand rather than clay (Figure 6). This is due to the higher permeability of granular soils, which allows injected materials to flow and distribute effectively, enhancing stability. In contrast, the low permeability of clay hinders uniform penetration, reducing injection efficiency (Hu et al., 2023).

Injecting materials like cement or nanomaterial slurries into sand and gravel improves cohesion, fills voids, and modifies soil structure. Nanomaterials enhance these effects due to their unique properties at the nanoscale, ensuring better distribution and stabilization (Jafarian Barough et al., 2022).

Figure 7 presents the percentage distribution of nanomaterials used in soil stabilization, regardless of the application method (standalone, mixed, or injection).

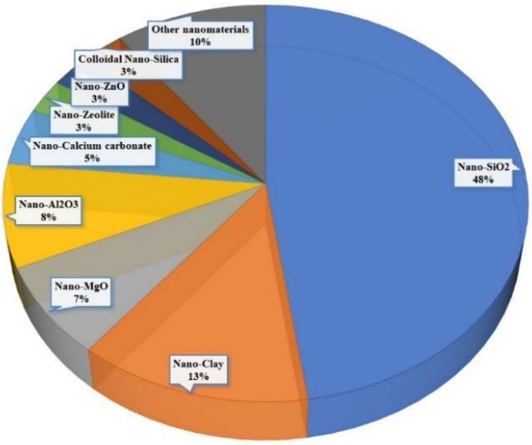

Figure 7. Distribution of nanomaterial types in soil stabilization

The findings reveal that nano-SiO_2 stands out as the most prevalent nanomaterial employed for soil stabilization, comprising 48% of the cases. Following closely are nano-clay and nano-Al_2O_3, with utilization rates of 13% and 8%, respectively. Hereafter, the primary characteristics of the three types of nanoparticles extensively utilized in soil improvement are elucidated.

Nano-Silica (SiO_2): Nano-silica (SiO_2), or silica nanoparticles, is widely used in various applications due to its nanoscale size, high surface area, and enhanced reactivity (Kakroudi et al., 2024; Lazaro, 2010). It is typically synthesized from silica precursors like tetraethyl orthosilicate (TEOS) or sodium silicate using sol-gel processes or chemical precipitation (Owoeye et al., 2021). The synthesis method influences the particle size, morphology, and surface properties. Nano-silica is extensively applied in materials science, construction, medicine, and electronics, enhancing performance in composites and formulations (Jan, 2019; Khan et al., 2022). In geotechnical engineering, it is among the most commonly used nanomaterials. Studies show that incorporating nano-silica improves the microstructure of cohesive soils, leading to increased compressive strength, reduced swelling, and enhanced shear strength.

Nano-Alumina (Al_2O_3): Nano-alumina is a versatile nanomaterial recognized for its high surface area, thermal stability, and excellent mechanical strength (Behera et al., 2016; Manivasakan et al., 2011). It is typically synthesized through controlled combustion of aluminum powder or hydrolysis of aluminum alkoxides, allowing for precise control over particle size and morphology (Thiruchitrambalam et al., 2004).

Nano-alumina has applications in catalysis, ceramics, electronics, and biomedical engineering due to its enhanced reactivity and surface activity (Nikoofar et al., 2019). In geotechnical engineering, nano-alumina is a promising material for soil stabilization. Studies indicate that its incorporation in cohesive soils enhances strength and durability, reinforcing soil structure, reducing shrinkage, and improving overall engineering performance.

Nano-Clay: Nano-clay consists of clay particles processed to nanoscale dimensions, typically within the nanometer range. Montmorillonite, a layered silicate clay, is among the most commonly used nano-clays. Characterized by a high aspect ratio, large surface area, and unique physicochemical properties, nano-clay is sourced through modification techniques such as intercalation and exfoliation (Kumar et al., 2022). Intercalation involves inserting organic or inorganic compounds between clay layers, expanding interlayer spaces, while exfoliation separates individual layers, resulting in nanoscale platelets. Nano-clay finds applications in polymer nanocomposites, coatings, and environmental remediation due to its ability to reinforce materials, enhance mechanical strength, improve thermal stability, and provide superior barrier properties (Batra et al., 2011). In geotechnical engineering, nano-clay particles such as montmorillonite and kaolinite have been studied for soil stabilization. Their addition improves soil structure, reduces permeability, and increases shear strength. Research suggests that nano-clay shows promise in mitigating issues related to expansive clays, enhancing overall soil performance (Sharo and Alawneh, 2016).

The dosage of nanomaterials plays a critical role in influencing soil behavior and project economics. Figure 8 details the distribution of nanomaterial dosages across reviewed studies. Most studies applied nanomaterials at levels below 10%, with some outliers using higher percentages (Ghadr et al., 2020; Liu et al., 2022; Wu et al., 2022). Additionally, certain studies determined nanoparticle content based on the replacement of other additives, such as cement and lime, in mixed approaches (Hussien and Albusoda, 2023; Pokkunuri et al., 2023), though this aspect is not explicitly explored in this section.

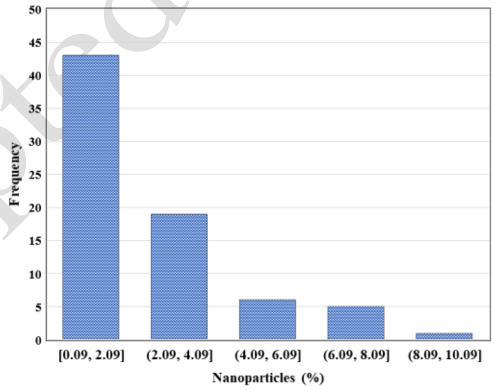

Figure 8. Histogram for nanoparticle dosage

The minimum value of the highest nanoparticle dosage reported in previous studies was 0.09% (Valizadeh and Janalizadeh Choobbasti, 2020). The histogram in Figure 8 shows that approximately 43% of studies utilized nanoparticles within the range of 0.09% to 2.09%, while 19% employed higher doses between 2.09% and 4.09%. The prevailing trend indicates that most studies used nanoparticles at concentrations below 5%, highlighting that even low dosages can significantly enhance the geotechnical properties of soils. This underscores the principle that a modest amount of nanoparticles can exert a substantial impact on soil stabilization without requiring higher percentages.

3.2. Using nanomaterials as standalone stabilizer for cohesive soils

Cohesive soils present significant challenges in civil engineering projects due to their high plasticity, shrink-swell behavior, and low permeability (McCabe et al., 2009). These soils are prone to volume changes with fluctuations in moisture content, leading to issues such as cracking and settlement that compromise the stability of structures (Puppala et al., 2007). Their low shear strength makes them susceptible to failure under applied loads, necessitating effective stabilization methods to enhance load-bearing capacity. Construction in cohesive soils is often hindered by weather sensitivity, resulting in delays, while the difficulty in excavation and inconsistent moisture conditions further add to project complexities. Moreover, the potential for long-term swelling, shrinkage, and diminished stabilization effectiveness poses durability concerns for civil engineering structures built on or within cohesive soils. Addressing these challenges requires tailored stabilization techniques to mitigate the adverse effects of cohesive soil characteristics on the performance and longevity of construction projects.

Nanomaterials offer a targeted solution by enhancing the cohesive forces between soil particles (Arabani et al., 2023). For instance, the utilization of nanoparticles, such as nano-silica and nano-alumina, enables a precise modification of the soil microstructure. These nanomaterials effectively mitigate issues related to swelling, shrinkage, and low shear strength in cohesive soils (Krishnan and Shukla, 2019). Tables 1 to 3 present a consolidated overview of outcomes from prior studies that employed nanomaterials as independent stabilizers for cohesive soil stabilization, accompanied by key findings. Tables 1 and 2 provide a summary of the key findings related to the use of nano-silica and nano-clay, two extensively employed nanomaterials in the stabilization of cohesive soils. Additionally, Table 3 presents information on various other nanomaterials utilized in soil stabilization.

Table 1. Summary of nano-silica impact on geotechnical properties of cohesive soils: key findings from prior studies

Authors	Soil Type	Key Results
García et al. (2017)	MH, CH	Adding 3% nano-SiO_2 to plastic clay increased UCS significantly, especially with higher water content. Nano-SiO_2 improved peak and residual stress in UCS, enhancing interlock forces and soil particle bonds.
Kong et al. (2018)	CL	Adding nano-SiO_2 gradually improved mechanical strength with increased content and curing days. Even a small addition can achieve full stabilization with sufficient curing time. The study highlights the close relationship between microscopic and macroscopic characteristics.
Buazar (2019)	CL	Nano- SiO_2 addition significantly improves key soil parameters, including plasticity, shear strength, cohesion, and CBR, with optimal improvement seen at 1.5% nano- SiO_2 content.
Kalhor et al. (2019)	CL	2% nano-SiO_2 stabilizes clay, raising moisture content, LL, and PL, but lowering γ_{dmax} and PI. Increased nano-SiO_2 induces brittleness; freeze-thaw cycles weaken strength.
Kalhor et al. (2022)	CL	Nano-SiO_2 improved soil plasticity, altered moisture content and density, decreased permeability, and enhanced triaxial strength, indicating a positive impact on the soil's physical and mechanical properties.
Sharma and Salhotra (2023)	CL	Addition of nano-SiO_2 led to increased Casagrande's limit and plastic limit, elevated PI, and reduced γ_{dmax}.
Hareesh and Vinoth Kumar (2016)	CL, CH	Higher percentages of nano- SiO_2 lead to increased ω_{opt} and decreased γ_{dmax}, improving soil shear strength.
Zomorodian et al. (2017)	CL	0.5–2.5% nanoparticle addition improved strength and stiffness. 1.5% nano-silica showed the best strength enhancement.

Table 2. Summary of nano-clay impact on geotechnical properties of cohesive soils: key findings from prior studies

Authors	Soil Type	Key Results
Abbasi et al. (2018)	CL, CH	Curing ages and nano-clay concentration significantly influenced stabilization, with 1% nano-clay at 3 days changing dispersivity to slight dispersive. 1% nano-clay was the most effective, improving soil classification.
Roustaei et al. (2023)	CL	The optimal nano-clay content of about 1% for increased compressive and tensile strength.
Khazaleh et al. (2023)	CL, CH	Nano-clay stabilization improved soft clay geotechnical properties, reducing permeability, increasing UCS, and controlling compressibility. Optimal dosages (0.15% for CL, 0.25% for CH) enhanced specific gravity and γ_{dmax}, creating impermeability.
Arabani and Shalchian (2023)	CL	Nano-clay stabilization significantly improves soil compressive strength, enhancing bearing capacity and particle interaction.
Zomorodian et al. (2017)	CL	0.5–2.5% nanoparticle addition improved strength and stiffness. 1% nano-clay showed the best strength enhancement.

Table 3. Summary of nanomaterials impact on geotechnical properties of cohesive soils: key findings from prior studies

Authors	Soil Type	Nano Type	Key Results
Coo et al. (2016)	CH	Nano-CuO Nano-Al_2O_3	Adding nano-CuO and γ- Al_2O_3 to clay significantly increases the shrinkage limit, reducing total volume reduction and potential cracking.
Naval et al. (2017)	CH	Nano-MgO Nano-Al_2O_3	Nano-MgO and nano-Al_2O_3 effectively reduce LL, PL, PI, and swelling potential while increasing γ_{dmax} in kaolinite clay.
Yousefi et al. (2022)	CL	Nano-Cement	Nano-cement increases shear modulus, lowers damping ratio, and improves shear modulus with higher percentages.
Mohammadi et al. (2022a)	CL, CH	Nano-Calcium carbonate	Optimal outcomes: 10% and 20% kaolinite and bentonite with 0.7% nano- $CaCO_3$, and 30% clay with 1.1% nano- $CaCO_3$, enhance UCS and consolidation properties.
Chen et al. (2022)	ML	Nano-MgO	The addition of 2.5% nano-MgO significantly improved the G_{max} of both pre-and post-freezing-thawing samples.
Hareesh and Vinoth Kumar (2016)	CL, CH	Nano-Silica Nano-Zeolite	Higher percentages of both nano- SiO_2 and nano-zeolite lead to increased ω_{opt} and decreased γ_{dmax}, improving soil shear strength, with nano-zeolite providing greater strength due to its mineral composition compared to predominantly SiO_2-based nano-silica.

Exploring the use of nanomaterials to enhance soil quality reveals a wealth of insights from numerous studies, highlighting the significant effects of introducing various nanoparticles into cohesive soils. Nano-silica, nano-zeolite, nano-CuO, γ-Al_2O_3, nano-MgO, nano-bentonite, nano-iron oxide, nano-calcium carbonate, nano-clay, and nano-aluminum oxide emerge as transformative agents, exhibiting diverse effects such as reducing shrinkage limit, enhancing settlement resistance, improving plasticity, increasing shear strength, and mitigating swelling potential.

Choosing the right nanomaterial becomes a strategic decision, dependent on the specific characteristics of the soil type and the intended purpose. A delicate ballet of effects unfolds, with optimal dosages customized to the nuanced interplay of soil properties and nanomaterial types. This collective evidence not only underscores the potential of nanotechnology but also emphasizes its ability to improve geotechnical properties across various applications.

Venturing into the microscopic domain, alterations in plastic properties—liquid limit (LL), plastic limit (PL), and plasticity index (PI)—come under scrutiny. Nanomaterials introduce fine particles, orchestrating a molecular-level interaction that modifies soil composition.

Integrating nanomaterials into clay soils usually leads to alterations, including an increase in ω_{opt} and variations in γ_{dmax} and plastic properties. The magnitude of these changes, whether an increase or decrease, hinges on the specific characteristics of both the clay and the added nanoparticles. The addition of nanoparticles to cohesive soils increases ω_{opt} due to improved packing, enhanced water adsorption on the higher surface area of nanoparticles, cohesive forces, and alterations in soil structure. Nanoparticles fill void spaces more effectively, leading to a reduced void ratio and an increase in ω_{opt}. The cohesive forces and altered microstructure further influence the water film thickness and engineering properties of the soil, collectively contributing to the observed rise in ω_{opt}. The impact of nanomaterials on γ_{dmax} in cohesive soils can vary depending on factors such as the specific characteristics of the nanomaterials and the soil type. Generally, the addition of nanomaterials can lead to an increase or decrease in γ_{dmax}. Nanoparticles may enhance soil compaction by filling void spaces, resulting in increased γ_{dmax} (Arabani et al., 2023; Karumanchi and Nerella, 2022). On the other hand, certain nanomaterials might alter the soil structure or induce agglomeration, potentially decreasing γ_{dmax} (Haji and Mir, 2023; Samala and Mir, 2020). The specific effects are contingent upon the interplay between the nanomaterials and the soil. Some previous research reported that the introduction of nanoparticles into the clay matrix triggers a noticeable shift in the fabric of the clay—manifesting a non-uniform and flocculated structure (Abbasi et al., 2018; Khayat et al., 2023). This phenomenon underscores the nuanced interplay between nanoparticles and the clay matrix, suggesting a pivotal role for nanoparticles in influencing the aggregation behavior of clay particles. These fabric changes, marked by non-uniformity and flocculation, unveil the complex interparticle forces and surface interactions at play, shedding light on the intricate mechanisms by which nanoparticles impact the fundamental structure of clay materials (Thomas and Rangaswamy, 2020a; Wang et al., 2015).

On the other hand, colloidal behavior undergoes a transformation, influencing the plasticity index by rebalancing cohesive and frictional forces. Nanomaterials can significantly influence the plastic properties, like PI, of cohesive soils. Adding nanomaterials to cohesive soils often leads to alterations in plasticity characteristics. By improving soil structure and particle interactions, nanomaterials can mitigate plasticity, reducing PI (Kalhor et al., 2022; Zeynali et al., 2023). Conversely, in some cases, adding nanomaterials may enhance cohesion and modify the soil matrix, leading to an increase in PI (Aksu and Eskisar, 2023; Kannan et al., 2023). The specific impact on plastic properties depends on the type of nanomaterials, their concentration, and their interactions with the soil matrix, underscoring the need for a nuanced understanding when employing nanomaterials for soil modification.

The narrative deepens as we delve into the Scanning Electron Microscope (SEM) results and the observed pozzolanic action, unveiling a finer and more uniform distribution of nanomaterial particles within the soil matrix. This microscopic transformation is not a mere visual spectacle; it is coupled with the pozzolanic alchemy between nanomaterials and soil constituents. The result is the formation of binding agents, such as calcium silicate hydrate (C-S-H), contributing to increased strength and durability.

Nanomaterials emerge not only as architects of structural change but as promoters of strong particle bonds, elevating cohesion, shear strength, and structural integrity (Seiphoori and Zamanian, 2022). Two interconnected mechanisms weave this part of the narrative. Firstly, the introduction of water to clay, facilitated by nanomaterials through double-layer water absorption, leads to the formation of a viscous gel (Ying et al., 2021). This gel, characterized by heightened viscosity, surpasses the bonding resulting from water absorption alone, acting as a binding agent that fosters stronger connections among clay particles (Changizi et al., 2022; Changizi and Haddad, 2016). Secondly, nanomaterials contribute to reducing the distance between clay particles, promoting increased contact, and a closer proximity that facilitates a greater number of clay particles coming into contact with each other (Kianersi et al., 2023). The bonding mechanism relies on the formation of a viscous gel induced by nanomaterials, effectively attaching clay particles. Direct shear test results validate this narrative, revealing that the cohesion of the stabilized soil surpasses that of the natural soil, indicative of an augmented effective interfacial contact area between clay particles with increasing nanomaterial content, leading to improved interfacial bond strength and associated friction in the stabilized soil (Ahmadi et al., 2024; Landman et al., 2014).

As the narrative progresses, the spotlight shifts to the significance of curing time on cohesive soils stabilized with nanomaterials—a critical aspect influencing the overall effectiveness of soil improvement (Meeravali et al., 2020). The pronounced impact of curing time directly influences the development of pozzolanic reactions between nanomaterials and soil constituents. A prolonged curing duration allows for more extensive chemical interactions, leading to enhanced binding agents like C-S-H, contributing to increased strength and durability (Mohammadi et al., 2022b). The temporal evolution of the soil's microstructure, as observed through SEM results, underscores the importance of adequate curing time in achieving a well-connected and compacted soil matrix. Insufficient curing may compromise the formation of strong particle bonds and the overall effectiveness of the stabilization process. Therefore, understanding and optimizing the curing time is crucial for maximizing the benefits of nanomaterial-induced improvements in geotechnical properties, ensuring long-term stability and performance of cohesive soils.

In this scientific endeavor, several mechanisms contributing to the observed increase in strength are proposed, as illustrated in Figure 9. The introduction of nanoparticles into cohesive soils initiates the formation of a viscous gel, enhancing cohesion among soil particles and consequently elevating shear strength. This gel formation typically occurs because of the interaction between nanoparticles and the existing water content in the soil. The nanoparticles, exhibiting high viscosity in the presence of water, transform into a gel or colloid with adhesive properties. This gel fills the micro-pores within the initially compacted soil, displacing water, and air. The alteration in the rheological properties of the mixture leads to increased adhesion among soil particles, augmenting shear strength. Simultaneously, nanoparticles play a crucial role in reducing the inter-particle distance within the soil matrix, effectively increasing soil density, and promoting extensive interconnection among soil particles. This reduction in particle spacing amplifies the contact surface area between soil particles, providing an additional boost to shear strength. These propositions align with previous studies (Bilgen and Altuntas, 2023; Ehwailat et al., 2022; Karimiazar et al., 2023; Shahidi et al., 2024), supporting the notion that the incorporation of nanoparticles significantly influences the microstructure and mechanical properties of cohesive soils.

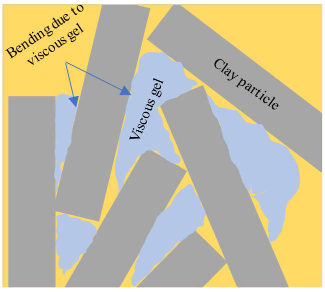

Figure 9. Formation of a viscous gel following the introduction of nanoparticles into cohesive soils

Several past studies have explored the enhanced durability of soils treated with nanomaterials when subjected to natural phenomena like wetting-drying and freeze-thaw cycles (Changizi et al., 2022; Khazaleh et al., 2023; Nourmohammadi et al., 2024). Freeze-thaw and wet-dry cycles significantly influence the mechanical behavior of geomaterials, constituting pivotal environmental factors that can alter the microstructure and mechanical properties of stabilized soils (Hadi Sahlabadi et al., 2021; Nourmohammadi et al., 2024). Freeze-thaw cycles, prevalent in cold climates, initiate a sequence of events wherein water within the geomaterial freezes, leading to an expansion in volume, and subsequently thaws, causing contraction (Y. Huang et al., 2022). This repetitive process can induce microcracks, fractures, and ultimately result in a reduction of the material's strength and cohesion. Additionally, the repetitive expansion and contraction cycles can induce significant alterations in the pore structure, thereby impacting the permeability of the material. These changes influence fluid flow pathways, affecting the hydraulic and drainage properties of the soil or geomaterial over time (Jamshidi et al., 2015).

Wet-dry cycles, driven by variations in moisture content, similarly play a pivotal role in the mechanical degradation of geomaterials (Li et al., 2023; Neramitkornburi et al., 2015). The absorption of water during wet phases can induce swelling, altering the material's volume and plasticity. Conversely, during dry phases, the loss of moisture can lead to shrinkage and cracking. These cyclic variations in moisture content significantly impact the material's compressibility, shear strength, and overall mechanical stability (Xu et al., 2021).

A thorough comprehension of the implications of freeze-thaw or wet-dry cycles, prevalent in regions affected by specific weather conditions, is imperative for engineering practices. This knowledge is crucial to ensure the durability and sustainability of structures constructed on or within geomaterials exposed to these environmental cycles. Previous studies indicated that the durability of cohesive soil against natural phenomena like freeze-thaw and wet-dry cycles improves with the addition of nanomaterials (Chen et al., 2023a; Shahidi et al., 2024). Nanomaterials contribute to enhanced soil stability and resilience through their pozzolanic action, strong particle bonds, and a more compact soil microstructure, preventing excessive water ingress and reducing vulnerability to environmental stressors. Nanomaterial-based soil stabilization plays a crucial role in mitigating the repercussions of water content fluctuations. By leveraging the unique properties of nanomaterials, this stabilization method promotes a more uniform distribution of forces within the soil matrix. The nanoparticles enhance the cohesion between soil particles, creating a stronger and more resilient structure that can better withstand variations in water content. This enhanced stability not only mitigates the risk of strength reduction and volume changes induced by freeze-thaw or wet-dry cycles but also augments the overall mechanical properties of the soil.

3.3. Using nanomaterials as standalone stabilizer for non-cohesive soils

Table 4 provides a comprehensive overview of results from previous studies that have employed nanomaterials as standalone stabilizers for non-cohesive soil stabilization, along with their key findings. A comparative analysis between Tables 1 to 3 and 4 reveals a predominant focus on cohesive soils in research concerning the use of nanoparticles for soil stabilization, as depicted in Figure 6.

Generally, construction on cohesive soils, known for their higher water retention and plasticity, presents more challenges compared to construction on granular soils (Al Heib et al., 2021; Ibrahim, 2016). Cohesive soils tend to exhibit greater sensitivity to changes in moisture content and can undergo significant volume changes. This poses challenges during excavation, foundation preparation, and overall structural stability (Day, 1994). The increased plasticity of cohesive soils can lead to difficulties in achieving proper compaction, potentially resulting in settlement issues over time. Moreover, the susceptibility of cohesive soils to swell and shrink with varying moisture conditions demands meticulous engineering solutions for foundations and structural elements to ensure long-term stability and performance. The challenges associated with cohesive soils underscore the need for precise construction techniques and soil stabilization methods to address their unique characteristics effectively. Conversely, granular soils, like sands and gravels, offer better drainage and compaction properties, resulting in a more stable foundation for construction. In the context of non-cohesive soils characterized by larger particles and lower plasticity, nanomaterials emerge as crucial agents for addressing issues related to compaction and shear strength (Huang and Wang, 2016; Jafarian Barough et al., 2022). The addition of nanoparticles to non-cohesive soils enhances water absorption potential, leading to an increase in ω_{opt}. Simultaneously, it raises γ_{dmax} by filling void spaces between soil particles (Karkush et al., 2020). Furthermore, integrating nanomaterials, akin to other stabilizers, leads to decreased compressibility and collapsibility potential, thereby mitigating risks linked to volumetric changes in the soil. Strategically incorporating nanoparticles improves interparticle bonding, thereby enhancing compaction efficiency (Ahmadi, 2021). These nanomaterials also contribute to lowering permeability and susceptibility to erosion in non-cohesive soils (Cheng and Saiyouri, 2018).

Table 4. Summary of nanomaterial impact on geotechnical properties in non-cohesive soils: key findings from prior studies

Authors	Soil Type	Nano Type	Key Results
Karkush et al. (2020)	SM, SP-SM	Nano-Clay	Adding nano-clay to gypseous soil increased γ_{dmax} and ω_{opt}. Nano-clay significantly reduced soil compressibility, with 2% considered optimal. It enhanced apparent cohesion and shifted soil collapse potential from severe to moderate at 4% nano-clay.
Ghadr et al. (2020)	SP	Colloidal Nano-Silica	Colloidal nano-SiO_2 impregnation improved yield and residual undrained shear strengths, mitigated excess pore water pressure, and induced more dilative, strain-hardening behavior.
Valizadeh and Janalizadeh Choobbasti (2020)	SC	Nano-Graphene	The research found a 73% improvement in self-healing of samples with 0.06% nano-graphene compared to samples without the additive at 28 days. SEM images confirmed the active role of nano-graphene in the self-healing process.

3.4. Combined application of nanomaterials and other additives in soil stabilization

The integration of nanoparticles and a diverse range of materials, including cement, lime, fibers, and waste, into soil and geomaterials represents a groundbreaking shift in geotechnical engineering methodologies (Yabaluie Khamesluei et al., 2024). This innovative approach emerges from a growing necessity to overcome the limitations of traditional soil stabilization and improvement techniques. By replacing conventional stabilizers, such as cement and lime, with nanomaterials in geotechnical applications, engineers unlock numerous advantages from both geotechnical and environmental standpoints. Geotechnically, nanomaterials offer the potential for superior soil stabilization, resulting in improved mechanical properties like increased strength, reduced permeability, and enhanced durability. The nanoscale particles contribute to enhanced compaction efficiency, fostering stronger interparticle bonding and reducing void spaces between soil particles, ultimately leading to increased shear strength and stability in geotechnical structures. From an environmental perspective, substituting a portion of traditional stabilizers with nanomaterials aligns with sustainability goals, often requiring lower quantities for effective soil improvement and contributing to reduced resource consumption and environmental impact (Firoozi et al., 2021). Additionally, the improved efficiency of nanomaterials in soil stabilization may lead to decreased carbon emissions associated with the production and transportation of traditional stabilizers. Overall, strategically incorporating nanomaterials as replacements for conventional stabilizers holds the promise of advancing geotechnical engineering practices toward more sustainable and environmentally friendly solutions.

3.4.1. Nanomaterials and cement

The widespread utilization of nanomaterials in conjunction with cement for soil stabilization is evident in the comprehensive studies detailed in Table 5. The amalgamated findings from these investigations not only underscore the broad acceptance of this approach but also illuminate its remarkable effectiveness. These investigations consistently reveal the favorable impact of nano-additives on UCS, shear strength, and durability across different soil types when combined with cement. The introduction of nanoparticles to cement-stabilized soil not only significantly bolsters compressive strength but also enhances splitting tensile strength and resistance to compressive deformation (Luo et al., 2022; Pateriya et al., 2022). Incorporating compound nanomaterials into cement-stabilized soil proves beneficial for both early and late-stage strength, mitigating corrosion speed, and optimizing soil compaction, particularly in marine environments (Chen et al., 2023a, 2023b).

When incorporating nanomaterials in conjunction with cement for soil stabilization, a multifaceted improvement in the structural properties emerges. Nanomaterials play a dual role by effectively filling the nanometer-scale voids in the soil and facilitating the formation of additional C-S-H. The utilization of nanomaterials, characterized by higher specific surface areas compared to cement, induces a heightened number of catalytic reactions, expediting the early-stage hydration processes. This acceleration, in turn, triggers subsequent pozzolanic reactions, fostering strong intermolecular bonds within the sample. The amalgamation of nanomaterials and cement results in a compact, durable, low-permeability composition that exhibits enhanced resistance to various environmental stresses. This synergy between nanomaterials and cement not only optimizes the mechanical and chemical properties of the stabilized soil but also contributes to the development of a robust and enduring infrastructure (Heidarizadeh et al., 2021). Previous research often identifies optimal replacement values for nanoparticles instead of cement. However, it's noteworthy that higher concentrations of nanomaterials in cement-stabilized soil may influence nucleation and crystallization, as observed in some studies (Mehairi and Husein, 2020).

The incorporation of nanomaterials provides a cost-effective and sustainable alternative for soil improvement. While cement has been a conventional choice for soil stabilization, its production contributes to harmful greenhouse gas emissions (Ghadir et al., 2021). Moreover, the use of cement often requires higher dosages, altering the inherent nature of the soil (Mousavi, 2018). Previous studies highlight the significant positive impact of substituting cement with nanomaterials on improving the geotechnical parameters of soils (Thomas and Rangaswamy, 2020b). These findings underscore the environmental concerns associated with cement production, including carbonation effects and the associated costs of carbon removal (Papadaki et al., 2018). Additionally, the combined treatment of cement and nanomaterials does not compromise drinking water pH standards (Kannan and Sujatha, 2022).

Table 5. Summary of nanomaterial impact on geotechnical properties in cement-stabilized soils: key findings from prior studies

Authors	**Soil Type**	**Nano Type**	**Key Results**
Luo et al. (2022)	Calcareous Sand	Nano-Silica	Nano-SiO_2 enhances compressive strength, optimum at 4.5%. It improves splitting tensile strength and compressive deformation resistance, showing a notable increase in modulus.
Liu et al. (2023)	CL	Nano-Silica	In summary, the study shows that adding nano-SiO_2 effectively enhances the strength of cemented soil. The UCS decreases rapidly with lower water-to-cement (w/c) values but stabilizes as the w/c value exceeds 7.
Mirzababaei et al. (2021)	CL	Nano-Silica Nano-Al_2O_3	Adding up to 1% nano-additives enhances UCS and shear strength in stabilized marl over time.
Yao et al. (2020)	ML	Nano-MgO	Both c and ϕ of cemented soil increased with higher cement content. For the investigated 10% cement content, the optimum nano-MgO content was 10%, resulting in peak cohesion.
Kulkarni and Mandal (2022a)	SM	Nano-ZnO	Adding 1.5% nano-ZnO to the soil significantly improved Soaked CBR values when treated with cement. UCS values improved with curing age, and Atterberg limits showed reduced soil plasticity.
Babaei et al. (2022)	SC	Nano-ZnO	Using Nano-ZnO as an additive improves the mechanical properties of cemented clayey sand. SEM images indicated a reduction in micro-cracks and moderated size and orientation of calcium hydroxide (CH) in samples with Nano-ZnO.
Kulanthaivel et al. (2021)	CL	Nano-Silica	The optimal dosage for nano-SiO_2 alone and white cement alone added to soil was 7% by weight of soil.
Yao et al. (2019)	CL	Nano-MgO	The study found that adding nano-MgO to cement-stabilized soil enhances strength and ductility, with an optimal nano-MgO content of 15% for 13% cement. Excessive nano-MgO may cause internal cracks.
Mollaei et al. (2023)	ML	Nano-Clay	Substituting nano-clay for cement increased shear modulus values, and damping decreased with added cement. Damping decreased at a lower rate when part of the cement was substituted with nano-clay.
Wu et al. (2022)	SP	Nano-Silica	Nano-SiO_2 (up to 8%) in cement-treated sandy soil enhances UCS but exceeding 8% reduces UCS due to hindered crystal growth and microcrack formation.
Kulkarni and Mandal (2022b)	SM	Nano-Silica	Optimal results were achieved for soil treated with nano-SiO_2 40% concentration and 6% cement, showing substantial improvements in soaked CBR and UCS values.

3.4.2. Nanomaterials and lime

The extensive application of nanomaterials combined with lime for soil stabilization is apparent in the detailed studies presented in Table 6. A comparison between Tables 6 and 7 reveals that the use of nanoparticles with cement as a stabilizer is more prevalent in research than the utilization of nanomaterials with lime. The popularity of cement over lime for soil stabilization can be attributed to several factors. Cement is known for its higher compressive strength and faster setting time compared to lime (Bayat et al., 2013). It provides effective stabilization in a shorter period, making it more convenient for construction projects with tight timelines. Additionally, cement is often considered more suitable for stabilizing cohesive soils, especially those with higher clay content. Lime may take longer to achieve optimal stabilization, and its effectiveness can vary based on soil types. Cement is also preferred in situations where high strength and durability are critical, such as in the construction of structures or road pavements. While both cement and lime have their applications in soil stabilization, the specific project requirements and soil characteristics play a significant role in determining the choice between them.

The incorporation of nanomaterials with lime in soil stabilization offers numerous advantages, as highlighted by significant findings in various studies. The addition of nanoparticles to stabilized soils with lime generally results in improved mechanical properties and enhanced performance. This combination proved effective for various road construction applications, including subgrade, subbase, and base layers.

The incorporation of nanomaterials with lime in soil stabilization offers numerous advantages, as highlighted by significant findings in various studies. This strategic combination leverages the unique properties of nanomaterials to enhance the effectiveness of lime in transforming soil properties. Nanomaterials, with their high reactivity and surface area, facilitate the dispersion and interaction with lime at a microscopic level (Khodaparast et al., 2021). This intricate interplay results in improved soil characteristics, including enhanced compressive strength, reduced plasticity, and increased durability. This process enhances the strength and stability of the treated soil. The catalytic action of nanomaterials accelerates the lime-induced pozzolanic reactions, promoting the formation of stable C-S-H gel (Karimiazar et al., 2023). At the microscopic level, nanoparticles facilitate robust bonds between soil particles, enhancing interparticle bonding and, consequently, increasing cohesion and shear strength in the stabilized soil. This microstructural adjustment within the soil subsequently results in enhancements in geotechnical properties and heightened durability of the amended soil. However, it is important to acknowledge that the brittleness of the treated soil experiences an increase (Akbari et al., 2021a; Mirzababaei et al., 2021).

Ultimately, the addition of nanomaterials to cement and lime for soil stabilization fosters a densely packed, well-connected microstructure, characterized by diminished voids, the formation of a viscous gel, and improved interparticle bonding. These microstructural enhancements contribute to superior mechanical properties, rendering the stabilized soil more resilient and capable of withstanding diverse environmental and load conditions (Karimiazar et al., 2023).

Table 6. Summary of nanomaterial impact on geotechnical properties in lime-stabilized soils: key findings from prior studies

Authors	Soil Type	Nano Type	Key Results
Jafari et al. (2021)	CL	Nano-silica	Adding nano-SiO_2 and lime to the mixture, up to certain levels (7% lime and 1% nano-SiO_2), significantly increased small strain characteristics and UCS of soft clay.
Jafari and Lajevardi (2022)	CL	Nano-silica	The addition of nano-SiO_2 (up to 1.5%) and lime (up to 7%) initially increased strength and stiffness in stabilized samples, followed by a decrease.

3.4.3. Nanomaterials and other additives

Furthermore, beyond nanomaterials use alongside the traditional stabilizers discussed earlier, nanomaterials have found application in conjunction with a diverse array of substances and techniques. These include the integration of nanomaterials with waste materials like rubber, slag, cement kiln dust, and waste fiber, as well as with fumes, fibers, lime, or cement combinations, MICP, and fly ash. Tables 7 to 11 offer a comprehensive summary of past studies integrating nanomaterials with supplementary additives, excluding the utilization of cement or lime. In summary, the diverse studies on soil stabilization using various combinations of nanomaterials and other additives reveal promising insights and practical applications.

The results presented in Table 7 demonstrate the efficacy of combining nanomaterials and waste products for soil improvement. The studies highlight innovative approaches to soil improvement by combining nanomaterials and waste products. These include the development of a robust, lightweight crust on calcareous lake sand using a mixture of ground rubber and colloidal nano-SiO_2. Stabilization of soft clay involves nano-modified cementitious binders reinforced with Basalt Fiber Pellets, showing notable enhancements in CBR, shear strength, and freezing-thawing resistance. Incorporating a mixture of Sewage Sludge Ash and cement, along with 1% nano-Al_2O_3, proves effective in improving UCS and CBR values. Optimal additions of 1% nano-SiO_2 and 15% silica fume enhance geotechnical properties, while treating clayey soil with 20% fly ash and 1.5% nano-SiO_2 significantly improves UCS and CBR values.

The utilization of waste materials or recycled materials for soil stabilization presents a sustainable and environmentally friendly approach to enhancing the engineering properties of soil (Bilgen and Altuntas, 2023; Roustaei et al., 2021; Salehi et al., 2023, 2021). By incorporating materials such as fly ash, slag, recycled plastic, or rubber into the soil matrix, it is possible to improve its strength, durability, and load-bearing capacity. These waste materials often contain pozzolanic or binding properties that react with the soil, creating a stable and compacted structure. This not only mitigates the adverse environmental impact of disposing of such materials but also reduces the dependence on traditional and often resource-intensive soil stabilization methods. Furthermore, the use of recycled materials promotes the circular economy by giving a second life to discarded resources (Bolden IV, 2013; Silva et al., 2019). As the world seeks more eco-conscious solutions, incorporating waste or recycled materials into soil stabilization practices stands as a promising strategy for sustainable infrastructure development (Onyelowe et al., 2019).

Table 7. Summary of nanomaterial impact on geotechnical properties in improved soils using nanomaterials and waste materials: key findings from prior studies

Authors	Soil Type	Nano Type	Other Additives	Key Results
Ghadr et al. (2022)	Calcareous Sand	Colloidal Nano-Silica	Rubber from waste tires	The study demonstrates that a mixture of ground rubber (GR) and colloidal nano-SiO_2 (NS) forms a strong, lightweight crust on calcareous lake sand.
Luo et al. (2012)	CL	Nano-Al_2O_3	Sewage Sludge, Ash, Cement	The study shows that incorporating 15% a mixture of Sewage Sludge Ash and cement significantly improves UCS and CBR values of untreated soil.
Ghavami et al. (2021)	CL	Nano-Silica	silica fume, cement kiln dust	Results indicated that 1% nano-SiO_2 and 15% silica fume were optimum additions for enhancing geotechnical properties.
Munda et al. (2022)	CH	Nnano-Silica	fly ash	The study found that treating clayey soil with 20% fly ash and 1.5% nano-SiO_2 significantly enhances the UCS and CBR values.

Combining waste materials or recycled materials with conventional stabilizers like cement, lime, or innovative nanomaterials offers a myriad of advantages for soil stabilization. This hybrid approach allows for the synergistic optimization of material properties, resulting in enhanced strength, reduced permeability, and improved compressibility of the stabilized soil (Bilgen and Altuntas, 2023; Salehi et al., 2021). The combination of different stabilizers enables a tailored and versatile approach, allowing engineers to adapt the stabilization process to meet specific soil conditions and project requirements. Overall, this integrated approach not only addresses the challenges of soil stabilization but also aligns with the growing global emphasis on eco-friendly construction practices and resource efficiency.

An additional additive that can be employed in conjunction with nanomaterials and synthetic stabilizers is the incorporation of both natural and synthetic fibers. The incorporation of fibers for soil improvement represents a transformative technique that brings numerous advantages to geotechnical engineering (Hadi Sahlabadi et al., 2021; Moslemi et al., 2022; Tavakol et al., 2023). Various types of fibers, such as polypropylene, polyester, and natural fibers, can be introduced into the soil matrix to enhance its mechanical properties (Subramanian et al., 2022). These fibers act as reinforcements, imparting increased tensile strength and reducing soil erosion (Hejazi et al., 2012). They also contribute to the mitigation of cracking and shrinkage in expansive soils, providing improved cohesion and strength (Z. Huang et al., 2022). Furthermore, fiber-reinforced soil exhibits enhanced load-bearing capacity, making it suitable for a wide range of construction applications (Rajeswari et al., 2019; Yetimoglu et al., 2005). The summarized findings in Table 8 demonstrate that the combined application of nanomaterials and fibers in soil improvement offers numerous benefits. For example, the results show that combining nano-SiO_2 and glass fiber mitigates thermal cycle effects in clay. The addition of recycled polyester fiber and nano-SiO_2 improves shear strength. Optimized mixtures, such as nano-SiO_2 with polypropylene or straw fiber, enhance compressive and tensile strength. The study highlights effective combinations like nano-$CaCO_3$ with carpet waste fibers for clayey soil and suggests nano-zeolite-fiber for lime-based stabilization. Overall, these approaches showcase efficient and sustainable soil improvement techniques.

Table 8. Summary of nanomaterial impact on geotechnical properties in improved soils using nanomaterials and fibers: key findings from prior studies

Authors	Soil Type	Nano Type	Fiber Type	Key Results
Kulanthaivel et al. (2022)	CH	Nano-Silica	Polypropylene fiber	Adding polypropylene fiber to poor soil increases density and reduces moisture content, while nano-SiO_2 in clay soil has the opposite effect.
Changizi and Haddad (2017b)	CL	Nano-Clay	Glass Fiber	Adding 0.5% to 1.5% nano-glass fibers and nano-clay significantly improves clay's mechanical properties, enhancing shear strength by up to 84%.
Ahmadi et al. (2021)	CL	Nano-Silica	Glass Fiber	A combination of 1% nano-SiO_2 and 2.5% glass fiber effectively enhanced the strength of clay, mitigating the negative effects of thermal cycles.
Arabani et al. (2023)	CL	Nano-Clay	Rice Fiber	The addition of 0.9% rice fibers improves soil ductility, shear strength, and failure strain. Microscopic analysis reveals enhanced particle-fiber interaction, forming a viscous gel.
Ahmadi et al. (2020)	CL	Nano-MgO	Polypropylene Fiber	0.2% nano-MgO enhances soil stiffness and cohesion by 45%, while Polypropylene fibers improve internal friction and ductility.
Lang and Chen (2021)	CH	Nano-Silica	Cement, Straw Fiber	Nano-SiO_2 increases UCS and splitting tensile strength, with the best content at 1.2%. Straw fiber decreases UCS but enhances splitting tensile strength (STS).
Sarli et al. (2020)	CL-ML	Nano-Silica	Recycled Polyester Fiber	The direct shear test demonstrated improved shear strength with higher contents of recycled polyester fiber and nano-SiO_2 in the soil mixture.
Choobbasti et al. (2019)	CL	Nano-Calcium Carbonate	Carpet Waste Fiber	1.2% nano-$CaCO_3$ enhances clayey soil strength. Combining 0.2% carpet waste fibers and nanoparticles further boosts strength.
Eshaghzadeh et al. (2021)	SM	Nano-Silica	Ceramic Fibers	Coating ceramic fibers with nano-SiO_2 enhances interfacial interaction in silty sand.
Lang et al. (2022)	Dredged sediments	Nano-MgO	Cement, Polypropylene Fiber	Nanomaterials significantly boosted the strength of cemented dredged sediment (optimal at 1.2%), with improved ductility and a strain-hardening effect when combined with polypropylene fibers.
Akbari et al. (2021b)	CL	Nano-Zeolite	Polypropylene fiber, Lime	Lime-nano-zeolite-fiber is suggested as a suitable modifier for lime-based stabilization in areas with wet-dry cycles.

The use of fibers in soil improvement not only strengthens the soil but also contributes to sustainable practices by utilizing recycled or waste fibers (Lim et al., 2023). This approach aligns with the broader goal of creating resilient and eco-friendly infrastructure, marking a significant advancement in the field of geotechnical engineering. In fiber-reinforced soil, a three-dimensional network is formed by the random distribution of fibers (Kou et al., 2021; Liu et al., 2020). This network links the surfaces of soil particles through friction and interlocking forces, as illustrated in Figure 10(a). The result is an enhancement in the tensile capacity of the soil/fiber mixture, as these forces work collectively to prevent fibers from sliding out of the soil matrix (Ayeldeen et al., 2022).

The synergistic combination of fibers and nanomaterials for soil stabilization represents a new approach with multifaceted advantages. By integrating fibers with nanomaterials, soil stability can be significantly enhanced (Cui et al., 2018). The fibers provide macro-scale reinforcement, improving the soil's mechanical properties such as tensile strength and load-bearing capacity, while nanomaterials contribute at the micro-scale by enhancing the soil's cohesion and reducing permeability (Ahmadi et al., 2021; Akbari et al., 2021b; Shalchian and Arabani, 2022). This dual reinforcement mechanism creates a more robust and durable soil matrix. The incorporation of nanomaterials additionally promotes enhanced interplay among soil particles and their distribution, thereby augmenting the overall efficacy of stabilizing agents. On the other hand, the combination of fiber, nanomaterials, and other stabilizers such as cement and lime has demonstrated superior outcomes compared to scenarios without nanomaterials. In the context of fiber, nanomaterials, and cement or lime, the penetration of nanomaterials into small voids around the surface of the fiber is a crucial aspect. Nanomaterials efficiently fill the micropores among soil particles and fibers, leading to a significant enhancement in bonding strength and interfacial force, resulting in an improved overall response (refer to Figure 10(b)). Figure 10(b) illustrates the presence of numerous cementitious products that adhere almost entirely to the main areas of the fiber surface. The filling of tiny voids with nanoparticles and the subsequent increased adhesion of soil particles to the surface of fibers reduce the likelihood of soil particle rotation. This, in turn, improves interlocking, friction, and interface bonding, facilitating the mobilization of tensile stress on the fiber unit. Additionally, this advanced combination allows for a reduction in the overall dosage of stabilizers, minimizing environmental impact and construction costs (Kannan and Sujatha, 2022; Karimiazar et al., 2022). The integration of fibers and nanomaterials not only addresses traditional challenges in soil stabilization but also paves the way for sustainable, high-performance geotechnical solutions in modern construction practices.

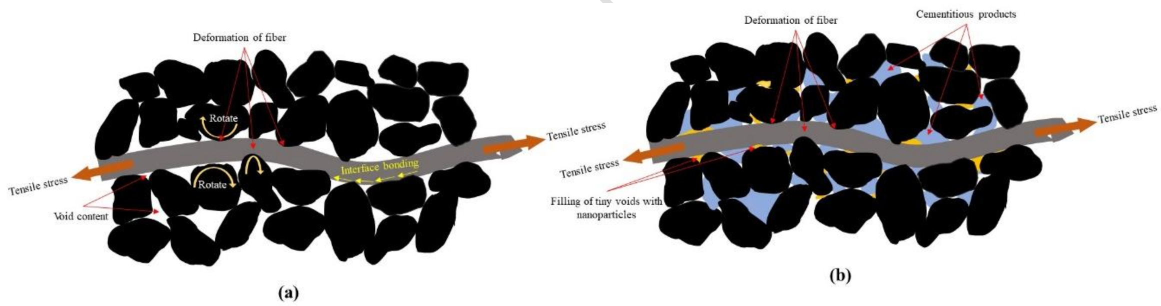

Figure 10. Schematic illustrating the contact conditions between soil particles and fiber: (a) without stabilizer, and (b) with stabilizer and nanomaterials.

As indicated in Table 9, the integration of nanomaterials and micromaterials in soil improvement has yielded notable outcomes. For instance, optimal proportions of lime powder and lime nanoparticles, around 4% and 1%, respectively, enhanced strength in tests. In another study, Nano-fly ash, at 7%, significantly increased UCS and triaxial strength, serving as a nano soil-improvement agent by forming a gel that fills pores and bonds soil particles. Nano-SiO_2, particularly below 2%, markedly enhanced soil compressive strength and elasticity. Utilizing a combination of nanomaterials and micromaterials for soil stabilization proves to be an effective approach. As the nanomaterial percentage increases, it leads to enhanced filling of soil voids and particles, thereby reducing soil porosity and improving interparticle bonds. In essence, voids of varying sizes between soil particles, from very small to large, are filled with a combination of nanomaterials and micromaterials. Nanomaterials efficiently occupy spaces that microparticles cannot, resulting in effective locking, interparticle bonds, and increased cohesion within the soil matrix. Consequently, this comprehensive interaction enhances the overall resistance of the soil.

Table 9. Summary of nanomaterial impact on geotechnical properties in improved soils using nanomaterials and micromaterials: key findings from prior studies

Authors	Soil Type	Nano Type	Micromaterials	Key Results
Tanzadeh et al. (2019)	CL	Nano-Lime	Micro-Lime	The optimal weight percentages for lime powder and lime nanoparticles were approximately 4% and 1%, respectively, leading to improved performance in strength tests.
Zeynali et al. (2023)	CL	Nano- Fly Ash	Micro- fly ash	The study found that adding 7% nano-fly ash and fly ash to soil significantly increased the UCS and the triaxial strength.
Ahmadi and Shafiee (2019)	CL	Nano-Silica	Micro-silica	Nano-SiO_2, especially below 2%, significantly improves soil compressive strength and elasticity. Higher nanomaterial amounts bring strength closer to micro-silica stabilized levels.

Table 10 demonstrates that integrating nanomaterials with other substances, including clays (such as kaolinite and montmorillonite), sodium silicate, diverse polymer and fiber combinations, and traditional stabilizers, enhances the efficacy of additives in soil improvement.

Table 10. Summary of nanomaterial impact on geotechnical properties in improved soils using nanomaterials and other additives: key findings from prior studies

Authors	Soil Type	Nano Type	Additives	Key Results
Mostafa et al. (2016)	CL	Nano-Silica	Lime, Silica Fume	Examining soil mixes with lime, silica fume, and Nano-SiO_2, changes occurred in properties like moisture content, density, plasticity, and swelling.
Eissa et al. (2023)	CH	Nano-Silica	Cement, Slag, Basalt Fiber and Polymer Pellets	Stabilizing soft clay with ternary mixtures of cement, slag, and nano-silica improves mechanical properties and frost stability.
Selvakumar et al. (2021)	CL	Nano-Silica	Sodium silicate	Adding nano- SiO_2 and sodium silicate improves clay soil strength. For example, 6% nano- SiO_2 increases UC strength by 422% and Young's modulus by 515%. This approach could benefit road pavement constructions.

Table 11 shows a summary of nanomaterial impact on geotechnical properties in improved soils using nanomaterials and the MICP technique. MICP is a bio-mediated geotechnical technique that harnesses the metabolic activity of bacteria to enhance soil stabilization (Fouladi et al., 2023). This innovative method involves introducing urea and calcium-rich solutions into the soil, providing a conducive environment for bacteria such as Sporosarcina pasteurii to metabolize urea, producing calcium carbonate as a byproduct (Bayat et al., 2021). This precipitation process results in the formation of cementitious compounds, binding soil particles and reinforcing the overall structure. MICP offers several advantages, including its eco-friendly nature, cost-effectiveness, and applicability to various soil types. By leveraging microbial activity, MICP contributes to improved soil strength, reduced permeability, and enhanced durability, making it a promising approach for sustainable soil stabilization in geotechnical engineering (Mujah et al., 2017).

The results of previous studies mentioned in Table 11 show that the combination of nanomaterials, bacteria, and cementation solutions led to increased calcium carbonate and UCS over time, as evidenced by SEM images revealing a flocculated soil texture with added nanomaterials. XRD analyses confirmed the presence of calcium carbonate, enhancing soil strength. However, the study observed that nano-SiO_2 inhibits the MICP reaction, promoting calcite formation in a solution environment but hindering it on quartz sand surfaces, resulting in vaterite formation. Overall, the presence of nanoscale silica particles is considered detrimental to MICP, indicating a nuanced impact on soil improvement.

Table 11. Summary of nanomaterial impact on geotechnical properties in improved soils using nanomaterials and MICP technique: key findings from prior studies

Authors	Soil Type	Nano Type	Key Results
Ghalandarzadeh et al. (2022)	CL	Nano-Silica, Nano-Calcium Carbonate	The addition of nanomaterials, bacteria, and cementation solutions increased calcium carbonate and UCS over time.
Liu et al. (2022)	SP	Nano-Silica	The study observed that nano-SiO_2 inhibits Microbially MICP reaction and promotes calcite formation in a solution environment. However, nano-SiO_2 inhibits calcite formation on quartz sand surfaces, resulting in vaterite formation.
Sangdeh et al. (2023)	SP	Nano-Silica	The results demonstrate the successful study of soil improvement using a combination of bacteria and nano-SiO_2.

In conclusion, the comprehensive findings from these studies underscore the versatility and efficacy of nanomaterials in soil stabilization, offering innovative solutions for diverse soil conditions and applications. The successful combinations and optimal concentrations identified in these studies provide valuable insights for engineers and researchers engaged in soil stabilization endeavors.

3.5. Application of nanomaterials as injection materials

Injection for soil improvement is a widely employed technique in geotechnical engineering aimed at enhancing the mechanical properties and stability of soils. This method involves the injection of various materials, such as cement grouts, resins, or chemical additives, into the subsurface to modify soil characteristics (Spagnoli, 2021). The injected material fills voids, reinforces soil particles, and improves overall cohesion and strength (Saleh et al., 2019). This process is particularly valuable for stabilizing loose or weak soils, and mitigating settlement issues (Sabri et al., 2021). Additionally, injection techniques are employed in ground improvement projects, foundation repairs, and slope stabilization efforts (Razuvaev et al., 2022). The versatility and effectiveness of soil injection make it a vital tool in geotechnical engineering for addressing diverse soil-related challenges and ensuring the durability and safety of civil engineering structures. The effectiveness of soil improvement through the injection method hinges on several critical factors that collectively determine the quality of the stabilization process. One pivotal factor is the selection of suitable injection materials, such as cementitious grouts or nanomaterial slurries, tailored to address specific soil conditions (Kazemain and Barghchi, 2012). The injection pressure and technique play a crucial role, in influencing the depth and distribution of the injected material within the soil matrix. Additionally, the soil's inherent characteristics, including its composition, porosity, and moisture content, impact the success of the injection method (Sabri et al., 2021).

The injection of nanomaterials for soil improvement represents an innovative approach in geotechnical engineering aimed at enhancing the geotechnical properties of soils at the nanoscale (Jafarian Barough et al., 2022; Mangifestaa et al., 2021). Nanomaterials are injected into the subsurface to modify the soil structure, providing benefits such as increased strength, improved stability, and reduced permeability. This technique enables the reinforcement of soil particles at a microscopic level, resulting in enhanced overall performance. The precision and targeted nature of injecting nanomaterials offer advantages in treating specific soil-related challenges, including issues related to weak or expansive soils. Utilizing nanomaterials in soil injection grout presents a distinct advantage, primarily attributed to the remarkable ease with which these nanoscale particles penetrate the soil matrix. This advantage stands out prominently when compared to traditional grouts like cement, as the extremely small size of nanomaterial particles allows them to effortlessly navigate through the intricate network of soil pores and fine cracks. The enhanced penetration capability of nanomaterials facilitates a more thorough and uniform distribution within the soil, maximizing their effectiveness in improving geotechnical properties. This unique characteristic not only streamlines the injection process but also holds the potential to address subsurface issues more comprehensively, providing a promising avenue for advancements in soil stabilization practices.

Table 12 provides a comprehensive summary of key findings from prior studies that utilized nanomaterials either individually or in combination with other materials as innovative injectable agents for soil applications. An inherent advantage of incorporating nanomaterials in soil improvement lies in their superior slurry penetration compared to traditional alternatives like cement slurry. This becomes particularly advantageous in scenarios where the penetration of conventional grouts faces challenges, such as dealing with extremely fine soils or other complicating factors. Nanomaterials offer a solution in such cases, as their fine particles enable enhanced infiltration. Moreover, the combination of nanomaterials with traditional substances, such as cement, in slurry preparation yields a mixture with heightened penetrating capabilities. This advanced slurry can efficiently navigate through the intricate network of fine pores within the soil, ultimately resulting in more effective soil improvement outcomes. On the other hand, the substitution of a portion of conventional materials, like cement, with nanomaterials in injection processes has led to a noteworthy decrease in the overall consumption of these materials, exemplifying an environmentally conscious approach.

Table 12. Summary of nanomaterial impact on geotechnical properties in improved soils using injection technique: key findings from prior studies

Authors	Soil Type	Nano Type	Additives	Key Results
Hussien and Albusoda (2023)	SP	Nano-Silica, Nano-Clay	-	Grouting nanomaterials in sandy soil increased shear strength, enhancing bonds. After 48 hours, internal friction angle significantly rose. Nanomaterials created a gel, filling voids and improving friction. Nano-clay and nano-SiO_2 increased cohesion.
Çelik et al. (2019)	SP	Nano-Silica, Nano-AL_2O_3	Cement, Silica Fume	Compressive strength increases with nanoparticles up to a certain point, but it plateaus or reduces afterward.
Kalhor et al. (2019)	MH	Nano-Silica	Lime, electrokinetics	Oedometer tests on samples treated with 3% lime and 5% nanomaterials show a substantial reduction in collapse potential, indicating improved stability.

Seiphoori and Zamanian (2022)	Collapsible soil	Nano-Clay	-	Study explores permeation grouting with montmorillonite clay nanoparticles for economical and sustainable soil enhancement.
Karkush et al. (2020)	SM, SP-SM	Nano-Silica, Nano-Clay	-	Low nanomaterial content enhances compressive strength, with significant improvement over time.
Boschi et al. (2024)	SP	Nano-Silica	Sodium chloride (NaCl)	The study developed an analytical model for nano-SiO_2 permeation grouting in water-saturated sands, employing a Binghamian model for rheology and a modified Darcy's law for seepage.

4. Future research needs

While the current body of research has made significant strides in unraveling the potential of nanomaterials for soil improvement, there remains a critical need for a more nuanced understanding of various parameters. Most studies have concentrated on fundamental aspects like compressive strength and shear strength, inadvertently sidelining other equally pivotal factors such as permeability and durability. These underexplored dimensions deserve heightened attention in future investigations to paint a comprehensive picture of the impact of nanomaterials on soil behavior.

Moreover, the bulk of existing literature leans heavily towards scrutinizing static parameters, neglecting a comprehensive examination of dynamic characteristics in soils treated with nanomaterials. This void underscores the necessity for future research endeavors dedicated to unraveling the intricate dynamics at play in these treated soils, both independently and in conjunction with other additives. Understanding how these materials respond under dynamic conditions is pivotal, particularly in earthquake-prone regions where liquefaction remains a critical concern. Delving into the influence of soil improvement, facilitated by the introduction or injection of nano slurry, on liquefaction susceptibility is paramount for enhancing seismic resilience.

Beyond seismic considerations, there exists a promising avenue for research in the realm of injection practices. Investigating the effectiveness and efficiency of novel materials, such as nanomaterials, as substitutes for conventional grouts like cement grout is imperative. This research avenue not only has implications for environmental sustainability but also for enhancing the overall efficacy of soil improvement techniques.

To unravel the underlying mechanisms driving the observed changes, in-depth studies focusing on the microstructure of soils improved using various materials will be instrumental. A comparative analysis, especially with soils improved using nanomaterials, can offer valuable insights, aiding in the interpretation of results and the formulation of more informed soil improvement strategies. In essence, future research needs to broaden its scope, embracing a holistic approach that encompasses the multifaceted intricacies of nanomaterial-assisted soil improvement.

Additionally, conducting an economic analysis comparing the use of nanomaterials for soil improvement against traditional additives holds significant relevance for geotechnical engineers in selecting materials for their projects. The financial implications of utilizing nanomaterials against traditional additives can play a decisive role in project planning and execution. Understanding the cost-effectiveness and potential savings associated with nanomaterial applications provides valuable insights for informed decision-making in geotechnical projects.

Moreover, evaluating the effectiveness of substituting nanomaterials for traditional additives in soil improvement contributes directly to the sustainable development agenda, a global priority. The environmental impact, resource utilization, and long-term sustainability aspects associated with nanomaterial use warrant thorough investigation. Geotechnical engineers, in alignment with the broader goals of sustainable development, can benefit from comprehensive studies that weigh the ecological footprint of nanomaterials against traditional alternatives. This nuanced understanding aids in aligning geotechnical practices with contemporary global sustainability benchmarks, ensuring environmentally responsible and forward-looking soil improvement strategies.

5. Summary

The review paper emphasizes the growing significance of nanomaterials in geotechnical engineering, particularly in soil stabilization. It explores their transformative benefits across diverse aspects of civil engineering, highlighting applications in concrete enhancement, corrosion resistance, thermal insulation, water treatment, and more. The integration of nanomaterials in geotechnical engineering offers promising solutions to address soil challenges and enhance structural stability.

The comprehensive review of 96 papers reveals three main approaches to nanomaterial use in soil stabilization: standalone application, combination with other materials, and incorporation as injection materials. The versatile use of nanomaterials across soil types, especially for clay soil enhancement and sandy soil injection, is underscored. The analysis highlights predominant nanomaterials like Nano-SiO_2 and their varied concentrations, emphasizing the substantial impact achievable with modest dosages.

In cohesive soils, nanomaterials like Nano-silica and Nano-alumina enhance microstructure, mitigating issues of swelling, shrinkage, and low shear strength. The microscopic changes and pozzolanic reactions contribute to increased strength and durability, with nanomaterial-induced improvements enduring natural phenomena. For non-cohesive soils, nanomaterials improve water absorption, increase optimal water content, and raise maximum dry density, addressing construction and stability challenges.

Integrating nanoparticles with materials like cement and lime enhances mechanical properties, reduces permeability, and aligns with sustainability goals. The synergy between nanomaterials and cement accelerates hydration processes, optimizing the mechanical and chemical properties of stabilized soil. Substituting cement with nanomaterials offers a cost-effective and sustainable alternative, contributing to robust and enduring infrastructure. Combining nanomaterials with lime in soil stabilization proves effective in road construction, improving compressive strength, reducing plasticity, and increasing durability. The integration of nanomaterials with various substances and techniques, such as waste materials, fibers, lime, cement, and MICP, demonstrates promising results for sustainable soil improvement.

Nanomaterial injection emerges as an innovative geotechnical method, efficiently penetrating soil pores and cracks, ensuring uniform distribution, and addressing challenges in weak or expansive soils. The targeted approach of nanomaterial injection proves precise and effective in geotechnical engineering for various soil-related challenges, reflecting an environmentally conscious approach. Overall, nanomaterials offer a versatile and effective solution for the complex challenges of soil stabilization in geotechnical engineering, promising a more sustainable and efficient future.

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