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Nanotechnology applied for soil stabilization – a survey

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ABSTRACT

The technical and constructive challenges inherent to the execution of engineering works on problematic soils require a continuous development or improvement of the techniques and methods used to investigate the soils' behavior and to design and evaluate the performance of these works. Soil stabilization is one of the most used techniques to improve the mechanical behavior of the soil. In addition to classic soil stabilization methods, nanotechnology is increasingly being used for various purposes, such as introducing nanoparticles of different compounds into the soil mixture or in the field of geosynthetics for fiber treatment. Although they do not have cementing properties, nanoparticles improve mechanical properties, thermal stability, and physicochemical behavior. Studies carried out with different types of soil show that introducing nanoparticles into the soil-cement matrix reduces the space between particles and provides a more robust and rigid soil skeleton. Considering this, it improves the material's resistance properties and reduces cement consumption, contributing to sustainability. The literature review presents research that evaluates different nanoparticles applied to soil mixtures and their influence on the final product. This paper reviews the state of the art of several studies showing that nanotechnology is a successful solution that can be used in soil stabilization because of its capacity to improve, for example, shear strength, unconfined compression strength, and the elastic modulus of soil. The research gap and prospects for using nanotechnology for soil stabilization are also exposed.

Keywords: Soil stabilization; nanotechnology; nanoparticles; overview.

1. Introduction

The constant territorial expansion in the world and the consequent scarcity of land favorable to construction have led engineers to seek alternatives for working with poor-quality soils (low strength and high compressibility). One of the most widely used techniques for improving the behavior and properties of poor soils is soil stabilization.

Based on the conditions of the natural soil, its initial properties, and the objectives required, the geotechnical engineer must choose between several possible soil stabilization techniques, which involve the physical or chemical modification of soils.

The traditional ground improvement techniques using cementitious materials to create a stronger soil mixture have limitations, especially in a sustainable context. The extensive cement production causes impacts related to energy consumption and environmental pollution. He et al. (2020) display that nearly 0.8 tons of CO_2 are released into the atmosphere per ton of cement produced.

With the urgency to explore novel materials that will reduce the problems cited above, in the recent decade, nanotechnology has become a new trend in all areas of science, and its different applications are being explored. This technology is based on reforming and processing materials into nanoscale to create better products. Nanoparticles refer to matter of dimensions of roughly 1 to 100 nanometers (NNI, 2007).

Nanotechnology is increasingly used in the field of civil engineering to improve the properties of different materials and make them more effective and economical. In the field of geotechnical engineering, pioneer studies are exploring the application of nanoparticles for soil stabilization.

This article presents a collection of various studies applying nanotechnology as a methodology for soil stabilization and the results achieved, comparing different materials and their characteristics.

2. Nanomaterials used in soil stabilization

Huang and Wang (2016) exposed that nanomaterials are pivotal in improving soil strength at both macro and micro levels. Soil strength, particularly under dynamic loading, is significantly influenced by pore water pressure in its composition as a three-phase medium with soil grains, water, and air. Macroscopically, nanomaterials reinforce the soil skeleton and modify pore fluid, impacting engineering properties. Microscopically, nanomaterials alter soil composition, structure, and particle interaction through size, microstructure, surface effects, and suspension rheology. These changes affect soil behavior, including plasticity and pore fluid properties, ultimately improving soil strength.

Nanoparticles are not cementitious agents, although when introduced into the soil they reduce the interparticle space and create a stronger and stiffer soil skeleton matrix. When incorporated with cementitious materials, nanoparticles can accelerate hydration kinetics, improve microstructure development, and decrease void volume within the matrix (Korpa et al., 2008; Ghazy et al., 2016). Compared to traditional grouting methods, nanoparticles promote soil improvement with less ground disturbance in a more cost-effective, sustainable way. In cementitious composites, nanoparticles like SiO_2, TiO_2, Al_2O_3, and carbon nanotubes are commonly applied for soil stabilization (Bahmani et al. 2014).

The nanomaterials can be divided into three categories considering their morphology due to the dimensions of the dispersed nanoscale fillers, as shown in Figure 1:

- Zero dimensional nanoparticles: nano-silica, nano-aluminum;
- One-dimensional fibers: carbon nanotubes;
- Two-dimensional sheets: nano-clay, graphene nanosheets.

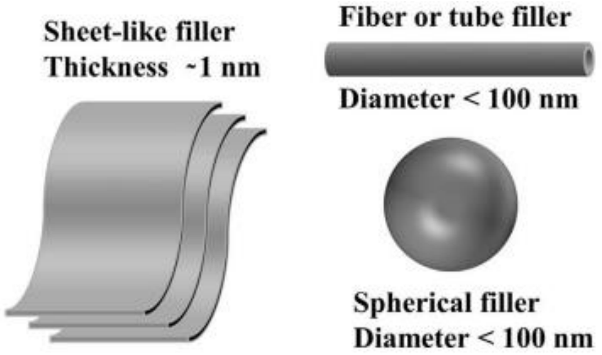

Figure 1. Three categories of nanomaterials (Fu et al., 2019).

In the following sections, these nanomaterials will be detailed, and several works found in the literature will be presented to state different applications of nanotechnology in soil stabilization.

2.1. Nano-silica

Nano-silica comprises very small particles of SiO_2, generally ranging from 7 to 22 nanometers linked through covalent hydrogen bonds. Its potential use in soils derives from the large amount of silica ions in its structure and an amorphous form, enabling pozzolanic reactions (Wang et al., 2020). This nanomaterial has high surface energy and can accelerate the hydration of cement; because of this, it is widely used in chemical stabilization. (ZHAO et al., 2019; BAHMANI et al., 2014). Different applications of nano-silica have been studied, mainly in cement-based materials, since they can improve their freshness, mechanical properties, and durability. Figure 3 presents an SEM image of nano-SiO_2 particles.

Experimental works have shown that the addition of 0.7% nano-SiO2 showed a maximum increase in compressive strength for cohesive soil and 0.4% for cement-treated residual soil (Changizi 2015; Bahmani, 2014). Salvatore et al. (2020), aiming to prevent liquefaction in sands, used nano-silicate grout and achieved satisfactory results because nano-silica forms a filler for the sand. Nano-silica can also increase the liquid limit (LL), plastic limit (LP), and optimum moisture content (OMC), as shown by Masrour et al. (2021). More detailed applications for nano-silica in various soil mixtures and for different purposes follow.

Heidarizadeh et al. (2021) examined the influence of nano-silica on the dynamic properties of cementitious soils, particularly on the maximum shear modulus Gmax. The authors conducted tests using a triaxial apparatus equipped with a pair of bender elements. The materials used included soft clay, nano-silica, Portland cement, and distilled water for samples.

The samples were cured at 22°C for 7, 28, and 56 days and then prepared with cement contents ranging from 0% to 15% and nano-silica contents ranging from 0% to 1.15% of the dry weight of the original soil. The results indicate that increasing the cement content and curing time increases the shear wave velocity, with nano-silica further enhancing this effect. A nano-silica content of 0.5% was considered optimal. Gmax can be calculated from the shear wave velocity. It was observed that increasing the cement content, nano-silica content, and curing time also increased Gmax. In contrast, adding nano-silica alone (without cement) does not affect the stiffness.

Frost-heave of soils is a phenomenon that negatively affects building structures. Aiming to find a method capable of reducing this problem, Zieba et al. (2019) studied the influence of the addition of both microsilica (MS) and nano-silica (NS) on frost-susceptible soils.

The tests were conducted with three variants: pure soil, soil with 5% MS, and soil with 5% NS. The results showed a reduction of the occurrence of ice lenses in the soil when micro-silica was added, and no frost-heave process was observed with the addition of nano-silica. Both stabilizers reduce the degree of freezing of the soil mixture.

Munda et al. (2022) stabilized a clayey soil with fly ash and nano-silica using percentages of 10, 15, 20 and 30% for fly ash by total weight of the dry soil and percentages of 0.5, 1.0, 1.5, 2.0 and 2.5% for nano-silica. CBR and UCS tests were conducted and the results found showed that the resistence enhanced significantly for the treated soil. Figure 2 presents results from the unconfined compresssion strength tests and it can be observerd that the optimum dosage was 20% of fly ash and 1.5% of nano-silica.

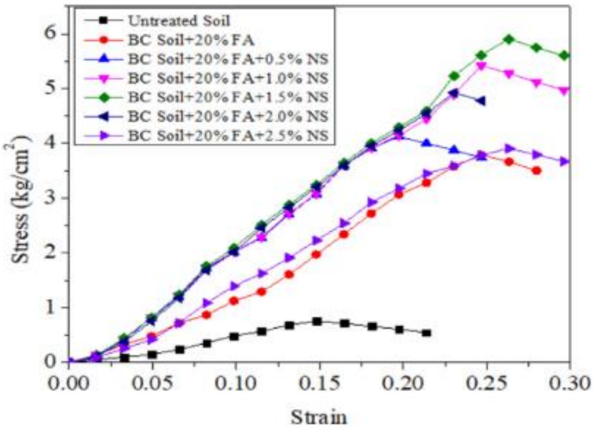

Figure 2. Stress strain behavior of optimum fly ash + nano-silica treated soil (Munda et al., 2022).

Aksu e Eskisar (2023) studied the effects of nano-silica on the geotechnical properties of soils when combined with cement. Atterberg limits, unconfined compression tests, direct shear tests and freeze-thaw tests were conducted on soil specimens treated with different percentages of cement and NS, showing changes in strength, Atterberg limits, and other properties over different curing periods.

The addition of nanosilica (NS) and cement to clayey soil resulted in significant strength improvements. Optimum NS content was found to be 0.5% for clay specimens. The UCS of untreated clay soil was 205 kPa, while it increased to 232 kPa with 0.5% NS. However, excessive NS addition reduced strength to 208 kPa, almost equivalent to untreated clay soil (205 kPa).

The addition of NS to sandy soil with cement showed significant strength improvement. The strength increased from 278 kPa with 0.3% NS to 648 kPa with 0.7% NS.

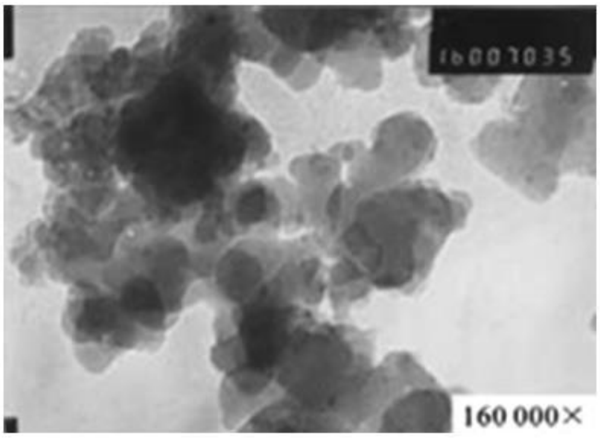

Figure 3. Nano-silica particles (Changizi and Haddad, 2016).

2.2. Carbon nanotubes

Carbon nanotubes (CNT) are made of graphene, a super-thin sheet of carbon that is the world's strongest particle. When the graphene is rolled into a tube, it forms a CNT (CHONG, 2004). In the context of multi-walled carbon nanotubes (MWCNT), attractive characteristics make them promising for applications in cementing systems. The ultrahigh-specific surface area of MWCNTs and their high yield strength and modulus of elasticity, contribute to an elastic behavior that can strengthen soil structure. However, an intrinsic challenge arises due to the natural tendency of these nanoparticles to aggregate, which can compromise the desired benefits. The limitation of using carbon nanotubes is their natural tendency to aggregate, which compromises their good properties. Correia et al. (2015) point out that surfactants or the application of ultrasonic energy are being explored to overcome this propensity for agglomeration. These approaches aim to efficiently disperse the nanotubes, ensuring a homogeneous distribution in the soil and maximizing the positive effects.

Correia et al. (2015) mixed silty soil with Portland cement and added MWCNTs in three quantities: 0.001, 0.01, and 0.1g. They used polycarboxylate-based surfactant to promote particle dispersion. Unconfined compressive strength (UCS) tests evaluated the mechanical performance of the chemical stabilization procedure. The results revealed a more ductile behavior than the reference tests, indicating a change in the soil's mechanical properties.

However, it is important to note that, despite the improvement in ductility, there was a decrease in the resistance of the samples to unconfined compression. This observation highlights the complexity of the interaction between nanoparticles and the soil matrix, underscoring the importance of an in-depth understanding to optimize the use of these innovative materials in cementing systems.

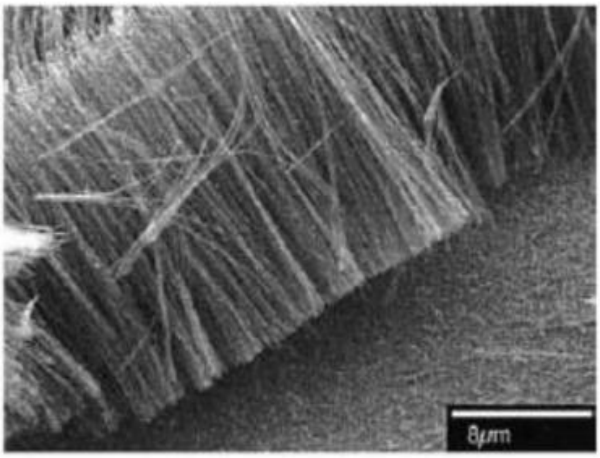

Figure 4. Multi-wall Carbon nanotubes (Fu et al., 2019)

2.3. Nano-clay

Several layers of mineral silicates, such as montmorillonite, bentonite, kaolinite, etc. constitute a nano-clay. It is produced from natural clays subjected to techniques that extract nanomaterials (Tabarsa et al., 2018). Nano-clay has a very high specific surface area, related to more water surrounding the particles. The accumulation of water in nano-pores decreases the bulk density. It has a higher specific surface area than nano-copper, nano-alumina, and nano-silica (Iranpour and Haddad, 2016).

Abbasi et al. (2017) investigated the treatment of low-plasticity and high-plasticity clay by adding different percentages of nano-clay. The results showed that the nano-clay particles reduced considerably the dispersivity potential of both types of soil, and the most effective was 1% of nano-clay added.

Tabarsa et al. (2018) examined the addition of nano-clay in loess soil, often eroded by water or wind. The authors ran various laboratory tests, including Atterberg limits, standard proctor compaction, unconfined compressive strength, unconsolidated undrained triaxial compression, wetting-induced collapse, and pinhole dispersivity. The addition of nano-clay to the loess soil increased the plasticity index and the optimum moisture content, decreased the maximum dry density, increased the total stress cohesion, and reduced the total stress friction angle, resulting in higher shear strength. A lower amount of erosion was observed by adding 2% of nano-clay.

Zomorodian et al. (2017) promoted an experimental investigation conducted on sandy lean clay (CL) soil to analyze improvements in strength and stiffness obtained by adding nanoclay and nanosilica materials as additives, considering varying curing periods. The results revealed significant soil strength and stiffness improvements with nanoparticle additions ranging from 0.5% to 2.5%. A more significant improvement in the clean CL soil's strength was achieved by adding 1% nanoclay or 1.5% nanosilica. Moreover, compared to nanosilica, nanoclay exhibited a lower optimal wt% requirement for clean and contaminated CL soil, indicating its better efficacy as a stabilizing agent.

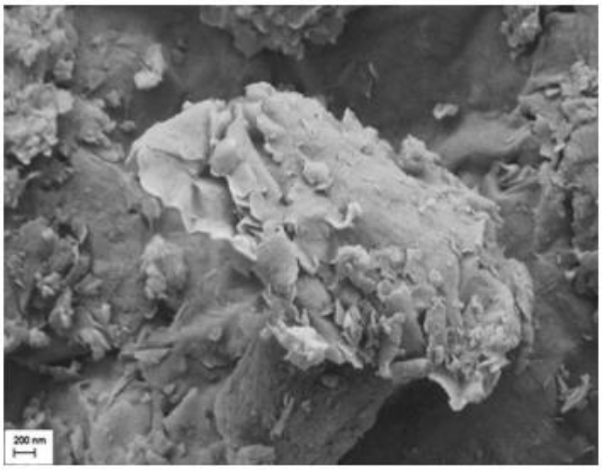

Figure 5. Nano-clay particle (Taha and Taha, 2012).

2.4. Other nanomaterials

Coo et al. (2016) studied the addition of two types of nanomaterials, nano-copper oxide (CuO) and gamma-aluminum oxide powder (γ-Al2O3), on clay to investigate the effect of desiccation-induced shrinkage. These materials were selected considering that both are insoluble in water and chemically stable. From an analysis of variance of the correlation between different percentages of nanoparticles, they concluded that adding 6% nano-CuO and γ-Al2O3 increases the shrinkage limit of clay by 17% and 8%, respectively. These results show that these nanoparticles can be used as soil additives for reducing soil shrinkage during desiccation.

Zimbardo (2019) investigated the effects of nanolime and an eco-polymer to improve the durability and efficacy of sand stabilization. Nanolime is formed by dispersions of nanoparticles of calcium hydroxide, often in ethanol and isopropanol. Taglieri et al. (2017) show that nanolime helps reduce porosity and water absorption by capillarity. The authors performed collapse tests, and for the treated samples, the Collapse Potential value, after 24h hours of soaking in water, was near zero. Also, the axial deformation was lower for the treated sand than the untreated sand. The compressibility and shear strength of the treated mixture was also evaluated. Zimbardo et al. (2019) concluded that nanolime prevented collapse, acting like a bonding agent and the stabilized sand showed improved mechanical behavior.

Babaei et al. (2022) investigated the variation of shear strength parameters of clayey sand treated with cement and nano titanium dioxide (NTD). Unconfined compression and direct shear tests along with field emission scanning electron microscopy (FESEM) were conducted to analyse the effects. The results from the FESEM images showed that NTD filled the holes and micro-cracks of the cemented sand. It was observerd that the optimum percentages for the most efficient mixture were 1.48% of NTD with 6.04% of cement and 20% kaolinite. This mixture presented cohesion of 215.3 kPa, friction angle of 49.78º and unconfined compression strength of 1.503 MPa.

2.5. Nanocomposites

Composites result from combining two or more materials, resulting in enhanced properties compared to each material used independently. In the context of soil composites, they are formed by a continuous matrix phase such as sand, silt, or clay; a dispersed phase, which may include reinforcements like fibers, geosynthetic materials, or particles, and the interface zone. When one phase presents nanoscale dimensios, they are called nanocomposites and have their properties improved. Usually is added to the matrix only 0.5 to 5% of nanomaterial by weight. Thomas et al. (2022) present different applications of nano-clay, nano-silica, nano-graphene, carbon nanotube and nano-calcium carbonate composites, which affect the microstructure, physical and chemical aspects of soil.

2.6. Innovations

Nanotechnology has risen as an interesting application in sensor development, particularly in the agricultural sector. Carbon nanotubes (CNTs), graphene, metal oxide nanoparticles (MONPs), and quantum dots (QDs) represent a suite of nanomaterials offering exceptional promise in the fabrication of highly sensitive, selective, and durable soil sensors (Parameswari et al., 2024).

Real-time monitoring facilitated by nanosensors, coupled with advanced data analytics, offers insights into soil health, moisture content, nutrient levels, and more, enabling informed decision-making for precision agriculture practices. With this technology, it will be possible to enhance agricultural productivity and optimize resource utilization, minimizing environmental impacts.

3. Research gaps and prospects

Like any other soil-stabilizing additive, the nanomaterials must be studied in depth since depending on the amount added, they can favor or harm the properties of the final mixture.

An analysis of the nanomaterials presented in this article reveals some inconsistencies found by the authors; for example, carbon nanotubes improved the ductility of the mixture and, on the other hand, decreased the resistance to unconfined compression. This fact highlights the need for further study into appropriate dosages so that the application of the nanomaterial does not harm one property, even if it improves another.

Other nanomaterials must be tested, and those already explored must be studied with different additives. Another point to be evaluated is the comparison between micro and nano size, in which situation each use provides more benefits.

Considering the research cited in this article, the direct influences of nanotechnology on costs and the environment have not yet been studied in depth. In the next few years, these materials will be characterized in a wide variety of environments and conditions, so that research can progress to the application and verification of the performance of nanomaterials in the field and under real circumstances.

4. Conclusions

Nanotechnology has found its application in all domains of science, particularly civil engineering and specific in geotechnical engineering. This technology has many advantages, including the fact that it is cost-effective, environmentally friendly, and does not create any disturbances. Using nanotechnology in soil stabilization for geotechnics is an exciting development and innovation within civil engineering. Nanotechnology is an innovative way of utilizing nanomaterials' characteristic properties for soil stabilization that can provide alternative solutions to the construction challenges in civil engineering and infrastructural development, such as the stability, strength, and durability of soils. The nanotechnological strategies can be implemented with these solutions, where among the most common applications include altering the physical and chemical properties of soil, decreasing permeability, and increasing bearing capacity, which are highly adaptable and sustainable solutions to a wide variety of geotechnical challenges. Continued research and development in this area promises to revolutionize construction practices, contribute significantly to mitigating geotechnical problems, and advance civil engineering toward a more resilient and efficient future.

In addition, it is important to highlight the role of specific nanomaterials exposed in this article used in soil stabilization, such as nano-silica, carbon tubes, and nano-clay. Nano-silica has proved effective in improving the mechanical properties of soils, increasing their resistance to compression, and reducing their permeability. Carbon nanotubes, with their exceptional strength and lightness, have been used to reinforce the structure of soils, providing greater stability in geotechnical applications. Due to its high surface area and adsorption capacity, nano-clay has been used to increase the cohesion and plasticity of soils, reducing their potential dispersivity, contributing to their stabilization, and preventing erosion. Incorporating these nanomaterials into soil stabilization techniques opens up many possibilities for optimizing civil construction and promoting more durable, safe, and sustainable infrastructures for future generations.

Finally, using the correct percentage of nanomaterial in soil stabilization is crucial to guaranteeing effective and safe results. The appropriate dosage of nanomaterial directly influences the physical and mechanical properties of the soil, such as strength, permeability, and plasticity. An excessive nanomaterial concentration can result in an excessively rigid soil mixture, leading to compaction problems and difficulties handling during construction. On the other hand, an insufficient percentage may not provide the desired stabilization benefits, leaving the soil susceptible to failure. It is, therefore, essential to carry out careful studies to determine the ideal proportion of nanomaterial for the specific characteristics of the soil and the requirements of the project, thus ensuring efficient and sustainable stabilization.

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