Journal of Advanced Sciences and Engineering Technologies (2025); 8 (1):1-27

DOI: http://doi.org/10.32441/jaset.8.1.4

Journal of Advanced Sciences and Engineering Technologies

www.jasetj.com

Journal of Advanced Sciences and Eng. Technologies

JASET

Nanomaterials for Soil Stabilization: A Review

Kawther G. Abd, Akram Hasan Abd

Civil Engineering Dept./ College of Engineering/Tikrit University /Tikrit, Iraq

Keywords:

Nanomaterials, Nano-silica, soil additive, weak soils, hydrophilic, gypseous soil, collapsibility.

Highlights:

- *Weak soils present major obstacles in construction due to their low strength and high compressibility. Conventional stabilization techniques, such as those using lime or cement, are often costly and pose environmental risks. Nanomaterials, however, have gained attention as a sustainable alternative to enhance the geotechnical properties of these soils.*
- *This review examines the use of nanomaterials like carbon nanotubes, nano clay, and nano-silica for stabilizing weak soils. It explores the interactions between these nanomaterials and soil particles, highlighting improvements in key properties including strength, stiffness, and permeability. The study also evaluates the environmental benefits and economic viability of these approaches.*
- *Nanomaterials prove effective for improving the performance of weak and metastable soils, such as gypseous soil. The review concludes that they represent a practical solution for geotechnical enhancement, while recommending further studies to refine their application and mitigate implementation challenges.*

ARTICLE INFO

Article history:

Received	21 July	2025
Received in revised form	15 Sep	2025
Accepted	20 Sep	2025
Final Proofreading	10 Oct	2025
Available online	20 Oct	2025

Corresponding author:

Kawther.G. Abd

Civil Engineering Dept./ College of Engineering/Tikrit University /Tikrit, Iraq.

Abstract: Weak soils, characterized by their low strength and high compressibility, pose significant challenges to construction projects. Traditional methods of soil stabilization often involve the use of lime or cement, which can be expensive and environmentally unfriendly. In recent years, nanomaterials have emerged as a promising alternative for improving the geotechnical properties of weak soils. This review study comprehensively investigates the application of various nanomaterials, including carbon nanotubes, nano clay, and nano-silica, to stabilize weak soils. The mechanisms of interaction between nanomaterials and soil particles are discussed, along with their effects on soil properties such as strength, stiffness, and permeability. Additionally, the environmental implications and economic feasibility of using nanomaterials for soil stabilization are considered. Based on the findings of this review, it is concluded that nanomaterials offer a viable and effective approach to enhance the geotechnical performance of weak soils and metastable soils such as gypseous soil. Further research is recommended to optimize the use of nanomaterials in practical applications and to address any potential challenges associated with their implementation.

INTRODUCTION

Soil is a natural substance made up of mineral particles that can be broken down from rocks through processes like weathering caused by water, air, or organic materials from decomposed plants. Another aspect to consider is that soil is the oldest and most cost-effective material used in construction. There is a growing need to utilize marginal areas for construction, including projects like city expansion and infrastructure development. However, some of these areas have weak soils that lack the necessary engineering properties. Consequently, it becomes imperative to improve and stabilize the soil to meet the engineering standards and transform it into a solid foundation for construction [1]. The importance of improving and stabilizing foundation soils has been recognized since the inception of construction projects, and over time, new solutions and technologies have emerged [2]. Soil stabilization refers to the methods employed to alter the texture of the soil and enhance its geotechnical properties. These methods aim at increasing shear strength, reducing permeability and compressibility, and ultimately enhancing the soil's bearing capacity. In general, there are two types of soil stabilization: mechanical and chemical [3]. Conventional stabilizers like lime, cement, fly ash, rice husk ash, magnesium oxide, concrete waste, petroleum products, iron furnace slag, and corn leaf ash have been utilized in numerous projects. Literature such as the references [4-11] has extensively studied their effects. In recent years, there has been a lot of interest in nanotechnology and nano-materials [12,13]. The use of nano-materials in soil enhancement was first explored in some earlier research. Regretfully, there hasn't been much research done in this area on how applying nano-materials can enhance undesirable geotechnical soil qualities. Recently, many attempts have been made to treat problematic soil using nano-materials for geotechnical and construction engineering applications, such as nano-silica, nano-alumina, and nano-cooper. The influence of nano-materials on the chemical and geotechnical properties of soils is more commonly investigated [14]. In addition, the use of nanomaterials has not been limited to soil improvement; they have also been utilized in the field of medicine. The latest and most important methods for synthesizing silver nanoparticles have been studied, in addition to the use of silver nanoparticles in various fields, especially those related to human life, such as medicine, drug delivery, and water purification [15]. Additionally, the composition, application, differences, and specific uses of carbon nanotubes were studied, with a brief presentation of the toxic effects of carbon nanotubes as well [16].

Many Nanomaterials (nano-silica, nano-clay, nano-copper, nano-carbon, etc.) were explored in geotechnical applications, and different types of soil (clay, soft clay, sand, and gypseous soil) were utilized. The aim of the studies below was to find the optimal ratio of nanomaterial required to improve soils. The current study presents the results of a systematic investigation on the impact of adding nanomaterials on the characteristics of soil, such as shear strength parameters, plasticity limit, compaction characteristics, and collapsibility. The previous research was presented in a chronological narrative style, and the reviews would be categorized according to the kind of soil.

NANOMATERIALS

The earliest recorded uses of nanotechnology date back to the BC era. More specifically, in Mesopotamia, the surface of the clay pots was found to contain traces of nanoparticles of copper and silver, which gave them a shiny appearance [17]. However, a solution made with a gold nanoparticle is said to have been the first scientific application of a nanomaterial in 1857 AD. Commercial businesses began using silica nanoparticles to strengthen rubber later in the 1940s. However, Richard Feynman originally highlighted the possibility of nanotechnology in a 1959 lecture titled "There is plenty of room at the bottom". Furthermore, it was in the 1970s when the word "nanotechnology" was first introduced, with the assertion that it primarily involved the processing of atoms and molecules [18]. Since the 1990s, nanotechnology has gained a lot of interest and has been progressively applied in many different industries, including chemical manufacturing, energy conversion and storage, biological applications, agriculture, and environmental technology [19-23]. Nanotechnology has a wide range of applications and potential benefits. In recent years, there has been a growing interest in using nanotechnology in Civil and Geotechnical Engineering. Specifically, researchers are looking at how nano-materials can improve soil parameters. The unique properties of nanomaterials, such as their high surface area and surface charges, can have a significant impact on the physical and chemical properties of soil. Nanoparticles have gained attention in various industries, including engineering, healthcare, and agriculture. Researchers are exploring ways to produce nanoparticles quickly, inexpensively, and in an environmentally friendly manner. These biosynthesized nanoparticles have properties that could benefit these industries [24]. Our understanding and appreciation of nanotechnology have grown in all fields of knowledge over the past 15 years. However, geotechnical engineering has been at the forefront of nanoscale research for quite some time. Geotechnical engineers have been working with materials and phenomena at the nanoscale long before nanotechnology became a mainstream topic [25].

This review paper discusses the major advancements in nanotechnology research and its applications in soil improvement. It also explores the important conclusions and implications of these advancements. Nanomaterials have been found to be effective in significantly enhancing the chemical and physical properties of soil. This is based on the principle of intermolecular overlap, which suggests that reducing the percentage of voids in soil can be achieved by using nanomaterials with different particle sizes. Various nanomaterials, such as nano-clay, nano-silica, nano-carbon, and nano-aluminum, are being used to improve the geotechnical characteristics of soil. The essay will provide an overview of current research on the use of these materials in geotechnical engineering.

LITERATURE REVIEW

Chronological order is used herein to present relevant previous studies. The reviews are categorized by soil type, with each group being explained separately:

Soft Soil

In 2012, Majeed and Mohd conducted a study on the impact of adding nano Cu, nano MgO, and nano clay to soft soil samples from Penang State. Different amounts of nanomaterials were added to the soil to analyze their effect on compaction, consistency limits, and compressive strength. Results showed improvements in geotechnical properties varied based on the type and percentage of nanomaterial added, with an increase in maximum dry density and a decrease in linear shrinkage and plasticity index. Unconfined compressive strength initially increased with nanomaterial content before decreasing at higher percentages. [26].

Majeed *et al.* (2014) studied the effect of three types of nanomaterials (nano-clay, nano copper, and nano magnesium) on soft soil. The percent of nanomaterials is less than 1% of the weight of the dry soil. The results showed a decrease in the plastic limit, liquid limit, plasticity index, and linear shrinkage. The dry density increased with the increase in the percentage of nanomaterials, and a decrease in the optimum moisture content with an increase in the percentage of nanomaterials. Also, the compressive strength increased with an increase in the percentage of nanomaterials[27].

Majeed *et al.* (2016) studied the effect of adding three types of nanomaterials (nano-copper, nano-alumina, and nano-magnesium) on soil. These nanomaterials were added in small percentages, not exceeding 1% of the dry weight of the soil. The results of laboratory tests indicated that the addition of nanomaterials led to an increase in both the dry density and unconfined compressive strength of the soil. Also, the moisture content of the soil decreased as the percentage of nanomaterials increased [28].

The impact of applying conventional materials and nanoparticles on the unconfined compression strength of soft soil is investigated by Al-Neami *et al.* (2021). Nano fly ash and nano silica fume for enhancing soil. To prepare the samples, nanomaterials are blended in a very small percentage (≤5%) by dry weight of the soil. According to the laboratory data, the additions have a detrimental impact on the unconfined compressive strength (UCS) of treated soil until it reaches the optimal number of nanomaterials, which is 3% percent. Additionally, when their magnitudes grow, the curing period has a significant impact on the unconfined compressive strength [29].

Clayey soil

Waychunas et al. (2005) studied the reactivity of nanoparticulate minerals such as goethite, akaganeite, hematite, ferrihydrite, and schwertmannite in soils, sediments, and mine drainage. These minerals have high sorption capacities for metal and anionic contaminants. Contaminant sequestration is mainly achieved through surface complexation, but aggregation of particles can affect contaminant dispersal and remediation processes. The study focused on the factors influencing the geochemical reactivity of nanophases and their ability to remove toxins from the environment, including recent findings on nanogoethite growth, aggregation, and sorption processes[30].

Fakhri et al. (2012) studied the effect of nano clay on clay's basic geotechnical properties by using Compaction and Atterberg Limits tests. The addition of nano clay was found to enhance the water absorption and flexibility of the samples by increasing their specific surface area and, as a result, the electrical load. As plasticity increases, it is expected that the permeability of the samples would decrease. These features are highly suitable and expected in the core of a mud dam [31].

Zahedi *et al.* (2014) conducted a study effect of nano-clay on the resistance of the exposed clay soils to freezing in vitro conditions. The findings indicate that adding 1.5, 3, 4.5, and 6 percent nano-clay will weaken soil during freezing cycles. This phenomenon may arise from the addition of nano-clay, which enhances the specific surface area of the samples. Consequently, an increase in electrical load leads to a rise in water absorption, which may be partially attributed to the ineffectiveness of increasing nano-clay for boosting soil resistance [32].

Changizi (2015), the effect of using recycled polyester fibers and nano-silica SiO2 as a stabilizer to enhance the mechanical properties of soil was investigated. Three different percentages of fiber soil (ranging from 0.1% to 0.5%) and three different formulations of nano-soil (with percentages ranging from 0.5% to 1%) were utilized. The results showed that the inclusion of recycled polyester fibers and nano-SiO2 improved the strength of the soil samples. However, increasing the content of nano-SiO2 led to a reduction in failure stress, while increasing the recycled polyester fiber content increased failure strain[33].

Irani et al. (2015) investigated the effect of graphene oxide nanosheets (GO) on the geotechnical properties of cemented soil. Different concentrations of GO were added to the soil to assess its impact on compaction characteristics, consistency limits, unconfined compression strength, and direct shear parameters. The addition of GO decreased plasticity and compressibility parameters while increasing tensile and shear strength. The unconfined compressive strength also increased with higher GO content. The study concluded that GO has a significant influence as a stabilizing agent on the mechanical properties of stabilized soil [34].

García and Trejo, et al. (2017) studied the effect of nano-SiO2 on clay soil. The results showed that nano-silica gives positive results on the mechanical properties of the highly plastic clay. It was the unconfined pressure that increased with the increase in the percentage of nanomaterial content. Also, the interlock forces between the nano-silica and soil particles are increased. Hence, using nano-silica might be an excellent additive for soil improvement [35].

Moghadas *et al.* (2018) studied the effects of nano-silica and silica fume on the microstructural and geotechnical parameters of kaolinite, a soft soil with low strength. The kaolinite clay was mixed with silica fume at 5%, 10%, and 15%. Also, the soil was mixed with nano-silica was percent at 1%, 2%, and 3% by dry weight of the soil. The result showed that silica fume and nano-silica fume increase the optimum moisture content and decrease the maximum dry density. Improved the values of the California bearing ratio by approximately two times compared to the raw soil, and improved the unconfined compressive strength [36].

Ghorbani et al. (2019) investigated the impact of nanospheres, specifically nano silica and nano zinc oxide, on the properties of clay soil. The results showed that the application of the selected nanospheres led to a significant increase in unconfined compressive strength (UCS) compared to untreated soil. After 28 days of treatment, the samples containing 6% lime and 1.5% nano-ZnO exhibited a 5-fold increase in UCS, while samples containing 6% lime and 2% nano-SiO2 experienced a 5.3-fold rise. Result in the highest mechanical strength in both UCS and California bearing ratio (CBR) tests. The results were further supported by scanning electron microscopy (SEM) analysis, which showed that the nanospheres promoted the formation of a dense and compacted matrix in the soil, leading to improved mechanical strength in the treated specimen [37].

Barbhuiya et al. (2020) studied the effect of nano-silica on silty or clayey soils on physio-mechanical properties and microstructural determination. The addition of nano-additives decreases plasticity, improves consolidation and compaction parameters, increases the elasticity modulus and California bearing ratio, but decreases the soil's specific gravity and hydraulic conductivity [38].

Thomas et al. (2020) studied the effect of cement and nano silica materials on soft clay. The combination of cement and nanoparticles improves compressive strength for soft clay. The particle size and bonding properties of the nano silica played a crucial role in enhancing the strength of the cement-soil mixture. With a size of 17 nm and a high level of reactivity, the nano silica fume increases soil strength in 28 days. Additionally, it was a 1% nano silica in cement gave an improvement be an effective formula for transforming soft clay into very hard clay [39].

Kulanthaivel *et al.* (2021) studied the effects of nano silica and polypropylene fiber on the shear strength and compaction parameters of clayey soil. The results show that when adding polypropylene fiber, to increases its maximum dry density and decreases the optimum moisture. While nano-silica is added to clay soil, the maximum dry density decreases and the optimum moisture content increases. Also, the addition of polypropylene fiber and nano silica to clay soil improves unconfined compressive strength. Clay soil's Young's modulus was increased by adding nano-silica and polypropylene fiber [40].

A study by Qu Jili et al. (2021) investigates the impact of nano titanium dioxide (TiO_2) on Shanghai clayey silt in the Yangtze River estuary. Results show increased liquid and plastic limits, decreased plasticity index, and improved acid-resistance. Nano TiO_2 can be used for soil improvement and sustainable development [41].

Ghazavi et al. (2022) study adds nano-silica to clay soil. Fine-grained soil was mixed with nano silica at concentrations of 1%, 2%, 3%, and 4% by dry weight of soil. The results show a decrease in the plasticity index, an increase in the maximum dry density, an increase optimum moisture content, and a reduction in the permeability coefficient. Also, triaxial unconsolidated undrained (UU) tests conducted on specimens treated with 2% nano silica and subjected to confining pressure showcased an additional maximum strength improvement ranging from 60% to 68%. Additionally, the cohesion and internal friction angle of the nano silica-treated specimen were higher compared to the untreated specimen [42].

Jassim et al. (2022) study adds nano silica for improving clay soil. The study showed that adding 0.4% to 0.6% of nano-silica gives the best result. The results showed that the addition of nano silica fume resulted in a decrease in the plasticity index, a decrease in the maximum dry density, and an increase in the optimum moisture content. Reduction in microstructural voids and improvement in the state of the clay soil due to the employment of nano-silica and improved stability of the soil [43].

Expansive soil

Sharma et al. (2017) studied the effect of two types of nanomaterials (nano magnesium oxide, Nano Al_2O_3) and added them in different percentages (0.5%, 1.0%, 1.5%, and 2.0%) to determine their effect on the properties of expansive soil. The result showed that the addition of these nanomaterials reduces swelling, making the soil more suitable for construction purposes [44].

Al-Swaidani *et al*. (2019) studied the effect of nano-calcined clay (NCC) and nano-limestone (NL) on the properties of expansive clayey soil. Three soil samples from three different sites were used for the study after being heated at temperatures of 450 °C, 650 °C, and 850°C for three hours. After that, they were mixed with 1% and 2% of nano-calcined clay and 0.6% of nano-limestone. The results of the study show improvement in the soil properties. Give percent 2% of nano calcined clay was added to the natural soil, the best result, the plasticity index (PI) decreased by more than 50%. Additionally, 0.6% nano limestone was introduced to examine the combined effect of nano limestone and nano calcined clay on the properties of clay soil. These two nanomaterials led to improvements in the soil used. For instance, the linear shrinkage and swelling pressure values decreased compared to those of the natural soil [45].

Firoozi et al. (2022), examined the impact of nano-lime, specifically at concentrations of 0.1%, 0.3%, 0.5%, 0.7%, 1.0%, 2.0%, and 3.0%, as well as lime at concentrations of 1%, 3%, 5%, 8%, and 10%, as chemical additives for enhancing expansive soil consisting of illite and kaolinite. It was observed that lower concentrations of nano-lime, specifically 1% for illite and 2% for kaolinite, resulted in a decrease in the plastic limit. In comparison, lime concentrations of 8% for illite and 5% for kaolinite produced similar effects. In summary, a smaller quantity of nano-lime (1-2%) can effectively enhance soil parameters [46].

Sandy soil

Choobbasti et al. (2015) studied the effect of nano-silica particles and synthetic pozzolanic materials on sandy soil. The added three different ratios of cement (5%, 9%, and 14% in relation to the dry weight of the sand) with four different ratios of nano silica (0%, 5%, 10%, and 15% in relation to the weight of the cement). These mixtures were then compacted into cylindrical samples. The findings suggested that the introduction of cement and nano silica resulted in enhancements in the engineering properties of the sand. As the cement content increased, there was a noticeable rise in the maximum dry weight of the sand. Moreover, when suitable amounts of nano silica were present, it significantly improved the mechanical characteristics of both the cement and the sand [47].

Baghban and Toufigh (2019) studied the effect of Taftan natural pozzolan and nanomaterials, such as nano-clay and nano-silica, to improve the stability of sandy soil. The results showed that mixing pozzolan and nanomaterials into the soil, in addition to increasing the amount of alkaline solution, increased the compressive strength of sandy soil. Furthermore, the strength of the geopolymer specimens showed improvement with the addition of nano-clay and nano-silica, up to a certain threshold of 2%, beyond which a decline was observed due to excessive accumulation of nanomaterials. Microstructural analysis revealed a significant chemical reaction between the additives and the formation of aluminosilicate gel in the geopolymer compounds. Also, improve the bearing capacity of the sandy soil. Therefore, the study suggests that natural Taftan pozzolan, nano-clay, and nano-silica offer suitable and advantageous alternatives for stabilizing earth structures [48].

Gypsum soil

Haddad and Iranpuor (2016) studied the effect of nanomaterials on collapsible soil Behavior. An appropriate specimen with collapse potential was employed to study the effects of nanomaterials on it. Specimens were treated with four types of nanomaterials (nano-clay, nano-copper, nano-alumina, and nano-silica) and mixed with different percentages of the dry weight of the soil. Soil tests were carried out on natural water content and density. The results showed that using nano-clay, nano-copper, nano-alumina, and nano-silica, various nanomaterials had different effects on the behavior of collapse soils [49].

Al-Gharrawi *et al.* (2020) studied the effect of nano-clay and nano-silica on the gypseous soil, known to be effective on the collapsibility of gypseous soil. The results showed that 1% of nano-silica can decrease the collapsibility by up to 91% [50].

Karkush *et al.* (2020) conducted a study on two gypseous soils, were subjected to laboratory tests. Nano-clay (NC) was used in three different concentrations (1%, 2%, and 4%) to enhance the chemical and geotechnical properties of the studied soils. The results showed that mixing nano-clay with gypseous soils affected the collapsibility behavior and permeability of the soils. The collapse potential decreased in gypsum soil for specimens mixed with 4% of nano-clay. The best percent to add nano-clay is 4% to improve of chemical and geotechnical properties of gypsum soil [51].

Almurshedi *et al.* (2020) investigated the effect of nano-silica fume NSF on the collapsibility and shear strength of gypseous soil before and after soaking. Three percentages of micro silica fume (1, 2, and 4%) are mixed with gypseous soil samples. By increasing the amount of nano-silica fume, the collapse potential of gypseous soil is lowered. Additionally, extending the curing period and adding more NSF led to an increase in soil shear strength [52].

Al-Obaidi *et al.* (2020) conducted a comparative analysis to evaluate the effects of silica fume and nano-silica on gypsum soil, which had a gypsum content of approximately 62%. The results indicated that adding silica fume (SF) and nano-silica fume (NSF) significantly enhanced the engineering properties of highly gypseous soils, in both dry and wet cases. When mixing the gypsum soils with 1-5% of nano-silica improved the friction angles were improved in both semi-dry and submerged conditions. Both SF and NSF reduced the risks associated with the collapsibility of gypseous soil. In fact, a mixture containing just 3% nano-silica yielded the best results [53].

ANALYZING THE RESULTS OF SOME STUDIES PREVIOUS RESEARCH

It can be noticed from the literature that many researchers have utilized different nanomaterials to examine the behavior of soil. A wide range of results is concluded for different types of soil and nano-additives. The following list of statements summarizes the results and highlights some valuable findings.

1. Adding Nano-SiO2 has improved the shear strength parameters of soft clay soil, Table 1.

2. Adding Nano-SiO2 has decreased the maximum dry unit weight and increased the optimal moisture content parameters of clay soil (Table 2).

3. Adding Nano-SiO2 and Nano-Clay has decreased the collapse potential of gypseous soil, Table 3.

4. Addition of nano-clay causes an increase in the apparent cohesion and internal friction angle of soil, both soaked and dry cases, Table 4. Also, adding nano-clay to gypseous soils increases the optimum moisture content and maximum dry density, increases specific gravity, and the addition of mixing of nano-clay causes a slight change in the coefficient of permeability of soil due to the reduction of the percentage of voids between soil particles, Table 5.

5. Mixing of nano-fly ash and nano-silica fume with soil causes an increase in the unconfined compressive strength (Cu); the best improvement rate was 3 % (Table 6.

SUMMARY

This paper summarizes previous studies by researchers (chronologically) since 2012 for the purpose of improving different types of soil using different types of nanomaterials. Table 7 summarizes the most important results obtained from previous studies, and most of them were improving clayey soil using nanomaterials. Since the type of soil has an important effect on its ability to bear the foundations of buildings, metastable soil may cause damage to the foundations of buildings due to its tendency to collapse when exposed to heavy loads, thus causing serious problems in geotechnical engineering. Nanomaterials have shown great potential in improving the mechanical properties of soil, such as strength, stiffness, and durability. The article provides an overview of various types of nanomaterials, including nanoparticles and nanotubes, and their applications in soil stabilization. The review also highlights the advantages of using nanomaterials, such as their high surface area, reactivity, and ability to improve soil properties at low concentrations. Additionally, the article discusses the challenges and prospects of using nanomaterials for soil stabilization. Overall, nanomaterials show promise as a solution for enhancing the performance of soils in engineering applications.

CONCLUSIONS

This paper provides a review of the use of nanomaterials as additives to soil and discusses the effects and results on the physical and mechanical properties of treated soils. Various types and percentages of nanomaterials, several conclusions can be drawn from them:

- It is important to remember that different conditions affect how nanomaterials behave, and Table 2 gives sufficient details on the outcomes of research using nanoparticles to stabilize soil.
- Because of their unique characteristics, such as their small size and high specific surface area, nanomaterials interact aggressively with molecules to generate a thick soil matrix.

- The geotechnical characteristics of soil can be significantly impacted by the presence of even minute amounts of nanomaterials. (Improve the properties of the soil).
- The kind of soil, the addition ratios, and the kind of particles all affect how different kinds of nanomaterials behave.
- Particle agglomeration brought on by a high concentration of nanoparticles degrades the soil's geotechnical qualities.
- We see that the cohesion, strength, shear strength, consistency limit, compressibility, collapse potential, and soil permeability of the soil mixture have all improved significantly as a result of the addition of nanomaterials.

In conclusion, the application of nanotechnology and nanomaterials as additives to soil demonstrates promise for improving soil properties. However, the selection of appropriate materials and their appropriate percentages should be carefully evaluated to achieve desired outcomes.

RECOMMENDATIONS

1. Explore the impact of nano-additives on the permeability and compaction characteristics of soil for construction applications.

2. Investigate the role of nanotechnology in enhancing the durability and resistance of soil against erosion and weathering.

3. Evaluate the effectiveness of nano-reinforcements in improving the load-bearing capacity and settlement behavior of soil for construction projects.

4. Investigate the environmental implications of using nanomaterials in soil stabilization and their long-term effects on soil quality.

5. Explore novel techniques for incorporating nanomaterials into soil to optimize their dispersion and interaction for improved engineering performance.

6. Investigate the economic feasibility and practicality of utilizing nanotechnology for enhancing the geotechnical properties of soil in construction applications.

Table 1 Shear strength parameters of clay stabilized with nano-SiO2. [35].

Specimens No.	*Nano-SiO_2 content (%)*	*Cohesion,c (kPa)*	*Angle of internal friction (degree)*

1	0	38	13.5
2	0.5	40.6	21.8
3	0.7	42.3	27.92
4	1	45	29.46

Table 2 Compaction characteristics of soil samples with different [42].

Specimens No.	*Nano-SiO_2 content (%)*	*MDD (g/cc)*	*OMC (%)*
1	0	1.44	18.2
2	0.2	1.42	18.8
3	0.4	1.41	19.2
4	0.8	1.36	20.3
5	1	1.38	19.6

Table 3 Results of single collapse test,[51].

Without treatment	*Treated with Nano-clay*					
	CP(%)	*%change in CP*	*CP(%)*	*%change in CP*	*CP(%)*	*%change in CP*
	2.5		5		10	
3.6	3.25	9.027	1.44	60	0.945	73.8
Without treatment	*Treated with Nano-silica*					
	CP(%)	*%change in CP*	*CP(%)*	*%change in CP*	*CP(%)*	*%change in CP*
	1		2		3	
3.6	1.537	57.3	2.45	32.0	0.945	73.8

Table 4 Results of shear strength parameters with curing period for natural soil specimen and soil treated with Nano clay, [52].

Soil	*Parameter*	*NC (%)*	*Before soaking (BS) Curing time, days*					*After soaking (AS) Curing time, days*				
			0	7	14	21	28	0	7	14	21	28
Soil	***Cohesion***	0	15	15	15	15	15	0	0	0	0	0

	kPa	1	17	19	22	25	30	3.5	4.8	5.9	7.5	8
		2	25	27	30	33	40	6	7.5	9	10.8	12.1
		4	31	32	35	41	48	7.8	9.6	12.5	13	15
	Angle of friction (degrees)	0	37.5	37.5	37.5	37.5	37.5	36	36	36	10.8	36
		1	37.8	38.6	38.7	39.2	39.5	36.6	36.8	37.9	36	38.3
		2	38.5	39.2	39.2	39.9	40.4	37	37.5	38.1	38.5	38.7
		4	39.1	39.6	40	40.5	40.8	37.5	38	38.8	39.1	39.5
Al-Samava Soil	*Cohesion kPa*	0	12	12	12	12	12	0	0	0	0	0
		1	15	17	19	23	25	2.7	3.8	4.9	6.5	7.5
		2	30	24	26	31	34	4.5	6.5	8	9.8	10.8
		4	27	30	33	42	46	6.5	8.6	11.5	12.5	14.0
	Angle of friction (degrees)	0	31	31	31	31	31	29	29	29	29	29.0
		1	33.2	34	35	36.5	37.5	30	30.6	31.2	31.7	32.4
		2	34.5	36	37.2	38.4	40	31.5	32	32.6	33	33.5
		4	35	37	38.5	39.7	41	32.4	32.8	33.6	34.4	34.9

Table 5 Physical properties of soil samples treated with NC,[52].

Soil	*NC %*	*Gs*	*MDD(kN/m³)*	*OMC (%)*	*k×10⁻⁴ cm/s*
Al-Najaf Soil	0	2.54	14.00	18	0.64
	1	2.60	15.98	22	0.52
	2	2.67	18.87	24	0.33
	4	2.72	20.12	30	0.21
Al-Samava Soil	0	2.48	13.40	18	0.83
	1	2.55	15.00	22	0.71
	2	2.62	18.66	24	0.54
	4	2.68	19.76	30	0.3

Table 6 Results of unconfined compression tests,[30].

Materials	*Parameter*	*Additive ratio (%)*	*Curing time, days*					
			0	1	3	7	14	28
Nano-flyash		0	7.16	9.89	20.20	20.33	20.39	23.5
	C_u	0.5	11.16	15.76	28.63	32.69	34.66	42.35
	(kPa)	1	17.41	22.29	38.45	38.75	39.01	42.47
		3	31.06	39.17	43.45	65.38	75.33	81.12

		5	17.67	22.42	41.59	50.96	51.8	58.84
Nano-silica fume	C_u (*kPa*)	0	7.16	9.89	20.20	20.33	20.39	23.5
		0.5	15.53	17.29	21.25	32.39	38.62	38.73
		1	22.19	22.85	33.73	36.65	40.6	57.95
		3	30.48	40.06	41.41	47.65	54.07	79.63
		5	20.20	24.74	32.99	37.89	51.49	68.68

Table 7: Current experimental research results

I	Researcher	Type of soil	Nanomaterial	Content (%)	Tests	Results: Increase	Results: Decreas	year
1	Majeed and Mohd	Soft	Nano- CuO Nano-MgO Nano-clay	0.05-1	Compaction	Maximum dry density, Optimum moisture content		2012
					Atterberg limit		L.L, P.L, P.I, Linear shrinkage	
2	Majeed et al.,	Soft	Nano copper Nano clay Nano -MgO	≤1	Compaction	Maximum dry density	Optimum moisture content	2014
					Atterberg limit		L.L, P.L, P.I, Linear shrinkage	
					Unconfined Compressive Strength	Compressive strength		
3	Majeed et al.,	soft	Nano-Alumina Nano- copper Nano- MgO	≤1	Compaction	Maximum dry density, Optimum moisture content		2016
					Unconfined compressive strength	Unconfined Compressive Strength		
4	Al-Neami *et al*	soft	Nano-flysh	≤5%	Unconfined compressive	Unconfined compressive		2021

					strength	strength		
5	Fakhri *et al*,.	Clay	Nano-clay	-	Atterberg limit Permeability	P. I	Permeability	
6	Zahedi *et al.*	Clay	Nano-clay	1.5-6	Compressive strength	Compressive strength		
7	Changizi	Clay	Nano-silica	0.5-1	Unconfined compressive strength	strength.		2015
8	Irani et al.,	clay	Nano graphene oxide	0-02-0.05	Atterberg limit UCS Direct shear	UCS Strength	P.I	2015
9	García and Trejo et al.,	Clay	Nano-silica	0.5-3	unconfined compressive strength	unconfined compressive strength		2017
10	Moghadas et al.,	Clay	Nano-silica fume	1-3	Atterberg limit Compaction Unconfined compressive strength California bearing ratio	P. L optimum moisture content compressive strength at 3 % CBR	L.L, P. I maximum dry density	2018
11	Ghorbani et al.,	Clay	Nano-silica Nano zinc oxide	1-2	Unconfined compressive strength California bearing ratio	UCS CBR		2019
12	Barbhuiya *et al*	Clay	Nano-silica	0.7-5	Shear strength	Cohesion	Angle of internal friction	2020

					Compaction	OMC	MDD	
					Unconfined compressive strength	UCS		
					California bearing ratio	CBR		
13	Thomas et al.,	Clay	Nano-silica	0.25-20	Atterberge limit		L.L, P.L, P.I	2020
					Unconfined compressive strength	UCS		
					Compaction	OMC	MDD	
14	Kulanthaivel *et al.,*	Clay	Nano-silica	0.2-1	Unconfined compressive strength	Unconfined compressive strength at 0.8 %		2021
					Atterberge limit		P. I	
15	Ghazavi et al.,	Clay	Nano-silica	1-4	Compaction	MDD OMC		2022
					Permebility		permeability coefficient	
					Atterberge limit	LL, PL	P. I	
16	Jassim et al.,	Clay	Nano-silica	0.1-0.8	Compaction	Optimum Moisture Content	Maximum Dry Density	2022
					Compaction	OWC	MBD	
17	Qu Jili	Clay	Nano- TiO_2	-	Atterberge limit	L.L, P.L	P.I	
18	Sharma et	Expan	Nano-MgO	0.5-2	Atterberg limit		L.L, P.L, P. I	2017

	al.,	sive	$Nano-Al_2O_3$		Consolidation		Swelling potential	
19	Al-Swadani *et al*,	Expan sive	Nano-calcined clay	0.6	Atterberg limit	L.L, P. L	P. I	2019
					Compaction	Maximum dry density		
			Nano-lime	1-2	Consolidation		Swelling potential	

I	Researcher	Type of soil	Nanomaterial	Content (%)	Tests	Results		Year
						Increase	Decreas	
20	Firoozi et al.,	Expansive	Nano-lime	0.1-3	Atterberg limit		L.L, P. L	2022
21	Choobbasti et al.,	Sandy	Nano-silica	5-15	Compaction	MDD OMC		2015
					Unconfined compressive strength	UCS		
22	Baghban Shokatabad	Sandy	Nano-clay Nano-silica	-	compressive strength	strength		2019
23	Haddad & Iranpuor	Collapse	Nano-clay Nano-copper Nanoalumina Nano-silica	-	Collapse		Collapse	2016
24	Al-Gharrawi et al	Gypsum	Nano-clay	2.5-10	Consolidation		collapse potential	2020
			Nano-silica	1-3				
25	Karkush, et *al*	Gypsum	Nano-clay	1-4	Compaction	MDD OMC		2020
					Compressibility		Compressibility at 2 %	

					shear strength	Apparent cohesion		
					Consolidation		Collapse potentia	
					Hydraulic conductivity		Hydraulic conductivity	
26	Almurshedi *, et al*	Gypsum	Nano Silica fume	1-4	Compaction	Optimum moisture content, maximum dry unit weight		2020
					Compressibility		Compressibility	
					Shear strength	Apparent cohesion, Angle of internal friction		
					Consolidation		Collapse potential	
27	Al-Obaidi, *et al*	Gypsum	Nano Silica	1-5	Shear strength	Apparent cohesion Angle of internal friction		2020
					Consolidation		Collapse potential	

ACKNOWLEDGEMENTS

The authors are grateful for the staff support of the Civil Engineering Department, College of Engineering, Tikrit University. Postgraduate Research No.TU.G/2022/(5073-7-3).

REFERENCES

[1] Shahin, S. S., Fayed, L. A. E., & Ahmad, H.(2015). Review of Nano additives in stabilization of Soil. *Seventh International Conference on Nano-Technology in conference.*

[2] Ivasuc, T., Olinic, E., & Manea, S.(2015). Mechanical behavior of destructurated expansive clay. *International Multidisciplinary Scientific GeoConference: SGEM, 2*, 581.

[3] Patel, A. (2019). Geotechnical investigations and improvement of ground conditions. *Woodhead Publishing*.

[4] Athanasopoulou, A. (2014). Addition of lime and fly ash to improve highway subgrade soils, *Journal of Materials in Civil Engineering*. 26(4) 773-775.

[5] Eberemu, A.O,. Tukka, D.D, and Osinubi, K.J. Potential use of rice husk ash in the stabilization and solidification of lateritic soil contaminated with tannery effluent. Geo-Congress 2014 *Technical Papers Geo-characterization and Modeling for Sustainability 2014,* 2263-2272.

[6] Abbas, Y. A., Ibrahim, M. N.,& Hussein, M. K. (2018). Effects of rice husk ash magnesium oxide addition on wear behavior of aluminum alloy matrix hybrid composites. *Tikrit Journal of Engineering Sciences*, *25*(4), 16-23.

[7] Zedan, A. J., Hummadi, R. A.,& Hussein, S. A. (2019). Effect of adding a mixture of (Concrete Waste and Asphalt Waste) on the properties of gypseous soil. *Tikrit Journal of Engineering Sciences*, *26*(1), 20-25.

[8] Abbas, J. K., & Al-Luhaibi, H.M., A.,(2020). Influence of iron furnaces slag on collapsibility and shear strength of gypseous soil. *Tikrit Journal of Engineering Sciences*, *27*(1), 65-71.

[9] Hamad, A. M., & Jassam, M. G. A. (2022). Comparative study of the effect of some

petroleum products on the engineering properties of gypseous soils. *Tikrit Journal of Engineering Sciences*, *29*(3), 59-69.

[10] Edeh, J.E,. Agbede, I.O,. and Tyoyila, A.(2014). Evaluation of sawdust ash–stabilized lateritic soil as highway pavement material. *Journal of Materials in Civil Engineering*, 26(2), 367-373.

[11] Kampala, S. A., Horpibulsuk, N. Prongmanee, and A. (2014). Chinkulkijniwat, A., Influence of wet-dry cycles on compressive strength of calcium carbide residue–fly ash stabilized clay. *Journal of Materials in Civil Engineering,* 26(4) 633-643.

[12] Brar, S. K., Verma, M., Tyagi, R. D., & Surampalli, R. Y. Engineered nanoparticles in wastewater and wastewater sludge–Evidence and impacts. *Waste management 2010*, *30*(3), 504-520.

[13] Ibrahim, R. K., Hamid, R., & Taha, M. R.(2012). Fire resistance of high-volume fly ash mortars with nanosilica addition. *Construction and Building Materials*, *36*, 779-786.

[14] Ghasabkolaei, N., Choobbasti, A. J., Roshan, N., & Ghasemi, S. E.(2017). Geotechnical properties of the soils modified with nanomaterials: A comprehensive review. *Archives of civil and mechanical engineering*, *17*(3), 639-650.

[15] Al-Saedy, M. A. E., Al Ameen B. O.A., Rulla. S., Hamed, W. M., & M. Dawood, M. K.(2020). Preparation method of Silver Nano particles. *Journal of Advanced Sciences and Engineering Technologies,* Vol.3 No 2, 1-8

[16] Abdullah, A. H., Mohammed, M. T., Khamis, W. M., & Abbas, B. F.(2018). Carbon Nano tube and it`s medical applications. *Journal of Advanced Sciences and Engineering Technologies,* Vol. 1, No.3

[17] Barhoum, A., & Makhlouf A.S.H.(2018). Emerging application of Nano-particle in architecture Nano-structure. *Chapter12, vol. in Micro and Nano Technologies.*

[18] Taniguchi, N., On the basic concept on nanotechnology, in proceeding intl. *Conf. prod. Eng. part I, Japan society of precision Engineering 1974*, Tokyo, Japan, 18-23.

[19] Gawande, M. B., Goswami, A., Felpin, F., Asefa, T., Huang, X., Silva, S., Zou, X., Zboril, R., Varma, R. S., & Chem. Rev. *Acs. chemrev 2016,* 116,3722-3811.

[20] Wu, Y., Ali, M. R.K., Chen, K., Fang, N., & El-Sayed, M. A., *Nano Today 2018*, 24, 120-140.

[21] Sun, M., Dong, H., Dougherty, A. W., Lu, Q., Peng, D., Wong, W., Huang, B., Sun, L., & C. Yan, *Nano Energy 2019*, 56, 473-481.

[22] Hochella, M. S., Mogk, D. W., Ranville, J., Allen, I. C., Luther, G. W., Marr, L. C., McGrail, B. P., Murayama, M., Qafoku, N.P., Rosso, K. M., Sahai, N., Schroeder, P. A., P Vikesland, P., Westerhoff, P., & Yang, Y., *Science 2019,* 363, u8299.

[23] Mitter, N.,& Hussey, K., *Nanotechnol.* 2019, 14, 508-510.

[24] Kajbafvala, A., M. Li., Bahmanpour, H., Maneshian, M.H., & Kauffmann,A.(2013). Nano/microstructured materials Rapid, low-cost and eco-friendly synthesis methods. *J. Nanopart,* (3), 530170.

[25] Taha, M. R., (2018), "Recent Developments in Nanomaterials for Geotechnical and Geo-environmental Engineering" *MATEC Web of Conferences* 149, pp 1-5.

[26] Majeed, Z. H., & Mohd, R. T.(2012). Effect of nanomaterial treatment on geotechnical properties of a Penang soft soil. *Journal of Asian Scientific Research,* 2.11, 587-592.

[27] Majeed, Z.H., Taha, M.R., Jawad, I.T.(2014). Stabilization of soft soil using Nanomaterials. *Research journal of applied sciences, Engineering and Technology,* 8(4): 503-509.

[28] Majeed, Z. H., & Mohd, R.T.(2016). The effects of using nanomaterials to improvement soft soils. *Saudi J Eng Technol*, 1.3, 58-63.

[29] Al-Neami, M.A., Al-Soudany, K. Y., & Tarsh, N. M.(2021). The Potential Influence of Using Nanomaterials Additives on Unconfined Compressive Strength of Soft Soil. *Earth and Environmental Science,* 856 – 012008.

[30] Waychunas, A. G. Christopher S. Kim., & Jillian F. B.(2005). Nanoparticulate iron oxide minerals in soils and sediments: unique properties and contaminant scavenging mechanisms. *Springer,* 409–433

[31] Fakhri. Z., R. Pourho seini, & Ebdi, T.(2015). Improvement in the Hydraulic properties of kaolinite with Adding Nano clay, *Amirkabir journal of science and research, civil and Environmental Engineering (ASJR-CEE),* 47 (3): 17-20.

[32] Zahedi, M., Sharifipour, M., Jahanbakhshi, F., & Bayat, R.(2014). Nanoclay Performance on Resistance of Clay under Freezing Cycles. *J. Appl. Sci. Environ. Manage,* 18(3) 427 -434.

[33] Changizi, F., & Haddad, A.(2015). Effect of Nano- sio2 on the Geotechnical properties of cohesive soil. *Geotechnical and Geological Engineering*, 34(2): 725-733.

[34] Irani, M., Naseria, F., & Dehkhodarajabi, M.(2016). Effect of graphene oxide nanosheets on the geotechnical properties of cemented silty soil. *Archives of Civil and Mechanical Engineering,* 695-701.

[35] Garcia, S., Treju, P., Ramirez, O., Lopez-Molina, J., & Hernandez, N.(2017). Influence of Nano silica on Compressive strength of lacustrine soft clays. *Proceedings of the 19th International conference on soil mechanics and Geotechnical Engineering, Seoul.*

[36] Moghadas, F. N., Ghavami, S., Farahani, B., & Jahanbakhsh, H. (2018). Effects of Silica Fume and Nano-silica on the Engineering Properties of Kaolinite Clay. *AUT Journal of Civil Engineering*, 2(2): 135-142.

[37] Ghorbani, A., shooiili, H. H., Mohammadi, M., Sianati, F., Salimi, M., Sadowski, L., & Szymanowski, J. (2019). Effect of Selected Nanospheres on the Mechanical Strength of Lime-Stabilized High-Plasticity Clay Soils. *Hindawi Advances in Civil Engineering*, ID 4257530.

[38] Barbhuiya, H. G., & Hasan, S. D.(2020). Effect of nano-silica on physio-mechanical properties and microstructure of soil: A comprehensive review. *Materials Today: Proceedings,* 2214-7853.

[39] Thomas,G., & Rangaswamy, K.(2020). Strengthening of cement blended soft clay with nano-silica particles. *Geomechanics and Engineering 2020* ,505-516.

[40] Kulanthaivel,P., Selvakumar, S., Soundara, B., Kayalvizhi,V.S., and Bhuvaneshwari, S.(2021). Combined effect of nano-silica and randomly distributed fibers on the strength behavior of clay soil. *Springer, Nanotechnology for Environmental Engineering*,41204-021-00176-3.

[41] Q, Jili., Yawen, Z., Weiqing, Q., Xiaoshun, Z., Hu Lingqing, & Cheng Jinrui.(2021). Nano titanium oxide for modifying water physical property and acid-resistance of alluvial soil in Yangtze River estuary. *Science and Engineering of Composite Materials*; 28: 169–179

[42] Ghazavi, M., Kalhor, A., and Roustaei, M.(2022). Impacts of Nano-silica on Physical Properties and Shear Strength of Clayey Soil. *Arabian Journal for Science and Engineering,* 47(4): 5271–5279.

[43] Jassim, N. W., Hassan, A. H., Mohammed, A. H., & Fattah, Y. M.(2022). Enhancement consistency and compaction characteristics of clayey soil using nano silica material. *Periodicals of Engineering and Natural Sciences 2022*, :77-83.

[44] Sharma, D., Sanjeev, N., &Chandan, K., (2017). Stabilization of expansive soil using nanomaterials. *Proceedings of the International Interdisciplinary Conference on Science Technology Engineering Management Pharmacy and Humanities,* Singapore.

[45] Al-Swaidani, A.M., Hammoud, I., al-Ghuraibi, I., Mezyab, A.(2019). Nanocalcined clay and Nano-lime as stabilizing Agent for Expansive clayey soil.

some Geotechnical properties, Advances in Civil Engineering materials, 8(3): 327-345.

[46] Firoozia, A. A., Najib, M., & Firoozi, A. A.(2022). Stabilization Expansive Clayey with Nano-Lime to Reduce Environmental Impact. *Jurnal Kejuruteraan,* 34(6), 1085-1091.

[47] Choobbasti, A. J., Vafaei, A., and Kutanaei, A. A.(2015). Mechanical Properties of Sandy Soil Improved with Cement and Nanosilica . *Open Eng*, 5:111–116.

[48] Baghban, R. S., & Toufigh, V. M.M.(2020). Stabilization of sandy soil with geopolymers based on nanomaterials and Taftan pozzolan. *Amirkabir J. Civil Eng*, 52(9), 579-582.

[49] Iranpour, B., & Haddad, A.(2016) The Influence of nanomaterials on collapsible soil treatment. *Engineering Geology,* 205: 40-53.

[50] Al-Gharrawi, A. M. B., Hayal, A. L., & Fattah, M. Y.(2020). Collapse problem treatment of gypseous soil by nanomaterials. *International Journal of Engineering*, *33*(9), 1737-1742.

[51] Karkush, M. O., Al-Murshedi, A. D., and Karim, H. H.(2020). Investigation of the impacts of nano-clay on the collapse potential and geotechnical properties of Gypseous soils. *Jordan Journal of Civil Engineering*, 14(4): 537–547.

[52] Al-Murshedi, A. D., Karkush, M. O., & Karim, H. H.(2020). Collapsibility and shear strength of gypseous soil improved by nano silica fume (NSF). *Key Engineering Materials*, *857*, 292-301.

[53] Al-Obaidi, A. A., Al-Mukhtar, M. T., Al-Dikhil, O. M., & Hannona, S. Q.(2020). Comparative study between silica fume and nano silica fume in improving the shear strength and collapsibility of highly gypseous soil. *Tikrit Journal of Engineering Sciences*, *27*(1), 72-78.