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Influence of Nano-TiO_2 Additives on the Swelling Behavior of Expansive Soils

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ABSTRACT

Expansive soils, rich in clay minerals, undergo significant swelling and shrinkage with moisture changes, often damaging foundations and infrastructure. To mitigate these challenges, ground improvement is essential, commonly achieved through chemical or physical stabilization methods.

Nanomaterials have recently emerged as promising stabilizing agents in geotechnical engineering. Their use bridges civil engineering, material science, and nanotechnology. Incorporating nanomaterials to reduce soil swelling is gaining attention as an innovative improvement technique.

This study presents an experimental investigation into the effect of Titanium dioxide (TiO2) on the swelling behavior of expansive soil. TiO2 were added at three different dosages (0.5%, 1.0%, and 1.5%) by dry weight of soil. The swelling characteristics of the natural expansive soil were first evaluated in its untreated condition, followed by an assessment of the influence of TiO2 through a series of one-dimensional odometer swell tests.

Swelling tests were conducted under a range of vertical pressures (50, 75, 100, 200, and 400 kPa) to quantify the changes in swell percentages and swelling pressure due to TiO2 treatment. The results contribute to a better understanding of the potential of nanomaterials, particularly TiO2, in mitigating the adverse effects of expansive soils in geotechnical applications.

1. Introduction

Soils that undergo significant volume changes in response to fluctuations in moisture content are commonly referred to as expansive soils, swelling soils, or shrink-swell soils. During periods of heavy rainfall, these soils absorb water, leading to expansion, reduced shear strength, and softening, which can compromise their load-bearing capacity. Conversely, in dry conditions, moisture loss causes the soils to shrink and harden, often resulting in surface cracking. Such cyclic volumetric changes pose serious challenges to infrastructure, including building foundations, pavements, drainage systems, and geo-environmental structures, especially in regions with pronounced seasonal variations [1]. Predominantly found in arid and semi-arid regions around the world, expansive soils present a substantial risk to human safety and structural integrity due to the severe damage they can cause when left untreated. These soils are responsible for billions of dollars in damages annually on a global scale, significantly affecting civil engineering infrastructure. The presence of certain clay minerals, particularly montmorillonite, is commonly associated with this problematic behavior. In areas where expansive soils are encountered, it is often necessary for engineers to implement ground improvement strategies to

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enhance the soil's engineering properties and ensure its suitability for supporting construction activities.

Soft soils are generally characterized by low shear strength and high compressibility. Among these, clay soils are particularly widespread across the globe and represent a major contributor to structural and infrastructure damage due to their pronounced volume-change behavior and limited load-bearing capacity [2–4].

To mitigate the adverse effects of desiccation-induced shrinkage in soils, various stabilization techniques have been developed, including the incorporation of additives such as sand, lime, and synthetic or natural fibers to enhance soil strength and reduce volumetric changes [5]. Numerous studies have explored the incorporation of external particulates to enhance the engineering properties of soils, focusing on improvements in strength, durability, and resistance to volume changes [6]. The incorporation of fibers, chemical stabilizers, geotextiles, and nanomaterials into soil has been shown to improve its engineering behavior by altering its physical and structural characteristics. In particular, chemical additives can significantly enhance the load-bearing capacity of expansive soils [7]. According to Al-Gharbawi et al. (2023), soil stabilization methods particularly those involving chemical additives such as lime or cement are critical for improving the engineering performance of expansive soils and reducing the risk of structural failure [8].

Although expansive soils often exhibit relatively high bearing capacity, their unstable volumetric behavior characterized by significant horizontal and vertical shrinkage and swelling can result in ground displacement, differential settlement, tilting, cracking, and, in extreme cases, structural failure of buildings [9–10]. Consequently, a thorough understanding of the engineering behavior of expansive soils is crucial, along with the development of effective methods to improve their performance.

The National Nanotechnology Initiative of the United States characterizes nanotechnology as the control and manipulation of materials having at least one dimension between 1 and 100 nanometers [11]. The contemporary definition of nanotechnology, grounded in the nanoscale criterion, is sufficiently broad to encompass research across nearly all natural science disciplines. This field transcends conventional boundaries, integrating diverse areas such as medicine, environmental science, energy, information and communication technologies, and heavy industry [12].

Nanomaterials exhibit a variety of remarkable properties, such as improved thermal conductivity, enhanced diffusion rates, superior mechanical strength, and the capacity to alloy metals that are typically immiscible [13–17]. The application of nanoparticles in geotechnical engineering remains an emerging technology, likely due to two fundamental reasons. The first issue is related to the expensive cost of the materials, the second reason deals with toxicity.

With continuous advancements in science and technology, researchers have begun leveraging nanoscale modifications to improve the efficiency and cost-effectiveness of geotechnical materials. The rapid progress of nanotechnology and its multidisciplinary integration has led to the incorporation of nanomaterials as additives aimed at enhancing soil strength. Despite these developments, the application of nanotechnology within geotechnical and geological engineering remains relatively limited, with most research still in its exploratory phase [18].

Owing to their extremely small size, nanoparticles are capable of infiltrating the microscopic pores within expansive soils, thereby effectively modifying their swelling behavior. Even in small quantities, nanomaterials can induce significant changes in both the physical and chemical properties of the soil [19].

In recent years, nanoparticles have attracted considerable attention due to their wide range of technological applications. Efforts have also been directed toward developing rapid, cost-effective, and environmentally friendly green synthesis methods. The beneficial properties of biosynthesized nanoparticles hold promising potential for applications in agriculture, biomedicine, and engineering fields [20]

The direct assessment of swelling properties in expansive clays is most reliably and conveniently performed using conventional one-dimensional consolidometers [21].

This study aims to investigate the effect of incorporating Titanium dioxide (TiO_2) on the swelling behavior of expansive soil. Specifically, the influence of varying TiO_2 content on key swelling parameters was evaluated to gain a deeper understanding of the role of nanomaterials in improving the engineering properties of expansive soils.

Nano-TiO_2 was selected due to its high chemical stability, photocatalytic activity, and strong surface reactivity, which enhance soil particle bonding and reduce swelling potential. Compared with other nanomaterials, it is more cost-effective, widely available, and less toxic, making it a practical and efficient choice for expansive soil stabilization.

The main focus of this paper is to review the use of nanomaterials, particularly Nano-TiO_2, in stabilizing expansive soils, highlighting their mechanisms, effectiveness, and potential as sustainable alternatives to traditional stabilizers.

2. Mechanisms of TiO_2 Nanoparticles in Soil Stabilization

Titanium Dioxide (TiO_2) nanoparticles, have gained attention due to their potential to enhance soil strength, reduce permeability, and improve overall soil quality. TiO_2 is a widely known for its high surface area, photocatalytic properties, and chemical stability. TiO_2 nanoparticles, typically in the range of 1–100 nm, possess unique characteristics such as high reactivity and the ability to form bonds with various soil components [22]. These properties make TiO_2 nanoparticles promising candidates for soil stabilization applications. The nanoparticles can interact with soil particles at a molecular level, leading to significant changes in the soil's physical and chemical properties.

Table 1 explores the mechanisms by which TiO_2 nanoparticles contribute to soil stabilization and the factors influencing their effectiveness.

Table 1: Explanation on the mechanism of TiO_2 in soil stabilization

Property of TiO_2	**Effect on Soils**	**Stabilization Process**	**Reference**
Surface area	**Particle bonding and plasticity**	TiO_2 nanoparticles, due to their high surface energy, bond strongly with fine soil particles like clay, resulting in improved compaction and reduced plasticity.	Yin et al. (2018) [18]
High reactivity	**Cementation with soil particles**	TiO_2 nanoparticles stabilize soil by forming cementing bonds with soil particles. In moist conditions, they react with hydroxyl groups on soil minerals to produce titanium-based compounds that enhance particle cohesion, thereby increasing the soil's strength and stiffness.	Rashad et al. (2020) [19]
Very small (Nano) size	**Soil permeability**	TiO_2 nanoparticles decrease soil permeability by filling voids between particles, hindering water flow. This is especially beneficial for highly permeable soils like sand, enhancing resistance to erosion and water infiltration.	Yin et al. (2018) [[19]]
Interactive ability with soils	**Bearing capacity and unconfined compressive strength**	TiO_2 nanoparticles enhance the soil's mechanical properties by increasing the unconfined compressive strength (UCS) of both fine-grained and coarse-grained soils. TiO_2 nanoparticles interact with hydroxyl groups on clay	Ghasabkolaei et al. (2017) [20]

minerals, forming new mineral phases that enhance soil stiffness, stability, and load-bearing capacity.

3. Material Properties

3.1 Soil

Undisturbed soil samples were collected from a depth of 1 meter below the ground surface in Al-Nasiriya city to minimize potential contamination from surface-applied chemicals and fertilizers. The expansive soil specimens were air-dried prior to testing. Soil classification was performed using particle size distribution and Atterberg's limits tests, conducted in accordance with ASTM D422 and ASTM D4318, respectively. Additionally, the standard Proctor compaction test was carried out following ASTM D698. A summary of the test results is presented in Table 2.

Table 2: Soil properties

Properties	Standards	Values
Natural water content, w_n (%)	ASTM D2216	28.202
Specific Gravity, G_s	ASTM D854	2.67
Sand (%)		10.8
Silt and Clay (%)		89.2
Liquid Limit, LL (%)	ASTM D4318	54
Plastic Limit, PL (%)	ASTM D4318	20
Plasticity Index (%)	ASTM D4318	34
Classification of soil	USCS	CH

3.2 Nanomaterials

In this study, the Nanomaterial (TiO_2) in powder form were procured from Amazon website, with the properties shown in Table 3.

Table 3: Properties of TiO_2

Property	TiO_2
Density (g/cm^3)	4.23
SSA (m^2/g)	35-65
Diameter (nm)	50
Purity (%)	>99
Color	White

4. Preparation of samples

The preparation of soil samples involved several steps. Initially, the natural expansive clay samples were air-dried, then manually crushed and passed through a No. 40 sieve. The sieved soil was dry-mixed with varying percentages of titanium dioxide (TiO_2) at 0.5%, 1.0%, and 1.5% by dry weight. To ensure uniform dispersion of TiO_2 nanoparticles, an ultrasonic device was employed during the mixing process. Since ultrasonic mixing is ineffective in dry conditions, the soil and nanomaterials were first blended with water to form a slurry. The ultrasonic device was then used to facilitate effective dispersion of TiO_2 within the soil matrix.

The general procedure for preparing the soil samples is outlined as follows:

1. Preparation of Ingredients: Accurately weigh the required amounts of soil and TiO_2 based on the desired dosage by dry weight.

2. Water Addition: Add water to the soil-TiO_2 mixture to reach the optimum moisture content (OMC), forming a uniform suspension suitable for dispersion.

3. Pre-Mixing: Perform preliminary mixing of the components either manually or using a magnetic stirrer to ensure initial distribution of the nanomaterials within the soil-water mixture.

4. Ultrasonic Dispersion: Utilize an ultrasonic device to break down nanoparticle agglomerations and achieve homogeneous dispersion of TiO2 throughout the aqueous soil matrix.

To mix nanomaterials with soil in water: 10 to 30 minutes is enough in most cases. To avoid heating the sample, playback can be used in batches (e.g.: 5 minutes Running, 1minute recess).

5. Test procedure

The effectiveness of TiO_2 stabilization was evaluated through one-dimensional (1-D) swell tests conducted on both untreated (control) and TiO_2-treated soil samples. In this test, the expansive soil samples, pre-mixed using an ultrasonic device at the specified optimum water content, were re-compacted in a standard mold in three equal layers to attain the desired density. The consolidation (odometer) ring, measuring 75 mm in diameter and 24 mm in height, was positioned within the mold. Particular attention was given to ensure that the specimen's height remained slightly below that of the ring, thereby maintaining lateral confinement throughout the swelling process.

The one-dimensional (1-D) swell test is employed to evaluate the swelling potential of soil under conditions of lateral restraint. In this test, soil specimens were statically compacted within a ring mold to 95% of their maximum dry density (MDD) at the optimum moisture content (OMC), resulting in samples with dimensions of 75 mm in diameter and 25 mm in height. Following a 24-hour curing period within the ring molds, the compacted specimens were subjected to one-dimensional swelling tests. To ensure stability during the testing process, the ring mold containing the soil specimen was placed inside a grooved consolidation cell. A filter paper was positioned above the specimen, while a porous stone was placed beneath it. Subsequently, a series of vertical loads (50, 75, 100, 200, and 400 kPa) were applied to the specimens.

Figure1. One-dimensional odometer apparatus

6. Result and Discussion

All specimens were tested using a one-dimensional odometer apparatus, with time-swell measurements systematically recorded. The results of the one-dimensional swell tests for both the untreated expansive soil and the TiO_2-treated soil specimens are presented in Table 4.

Figure 2 compares untreated soil with soils treated with 0.5%, 1%, and 1.5% TiO_2, highlighting how the addition of TiO_2 affects deformation under increasing stress.

The untreated soil exhibits the highest swelling, with positive vertical deformation (ΔH) peaking at approximately 0.359 cm before gradually transitioning to settlement under higher stress levels. When 0.5% TiO_2 is added, the swelling is reduced compared to untreated soil, but significant positive deformation is still observed. At 1% TiO_2, a clear improvement is evident, as the swelling becomes minimal and the soil transitions to compression more rapidly. The best performance is achieved with 1.5% TiO_2, where swelling is almost completely eliminated, and the soil maintains consistent slight compression throughout the entire stress range.

When TiO_2 nanoparticles are introduced, a noticeable reduction in swelling is observed, particularly at higher dosages. The improvement can be attributed to several mechanisms. First, TiO_2 nanoparticles fill the micro- and nano-pores within the clay matrix, thereby reducing the available void space for water adsorption and penetration. Second, these nanoparticles enhance particle packing and lead to a denser soil structure, which limits the movement and expansion of clay platelets.

Thus, TiO_2 (especially at 1.5%) proves to be a highly effective additive for stabilizing expansive soils, making it ideal for improving soil performance in geotechnical applications such as foundations and embankments.

Table 4: The results of swell tests

Stress (kPa)	Swelling (%)	TiO_2 (%)
50	14.68781	0
	0.128733143	0.5
	0.033556638	1
	0.006743341	1.5
75	12.70116	0
	0.115630182	0.5
	0.045399099	1

	0	1.5
	11.60118	0
100	0.083126844	0.5
	0	1
	0	1.5
	7.379354	0
200	0.049719983	0.5
	0	1
	0	1.5

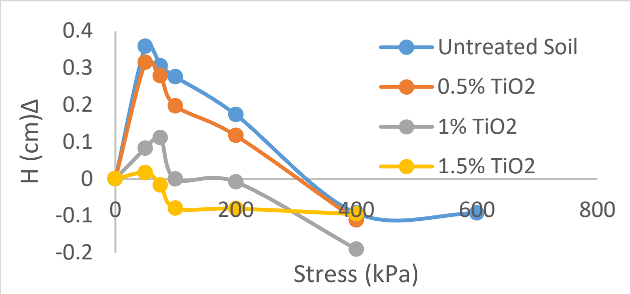

Figure 2: The relationship between ΔH (cm) of the soil samples with adding different percentages of TiO_2 and the applied loads (kPa)

Figure 3 shows the effect of varying percentages of TiO_2 on the swelling percentage of a material reinforced with TiO_2 under different stress levels (50, 75, 100, and 200 kPa).

At 0% TiO_2, swelling is observed to be the highest for all stress levels, with the highest swelling (14.69%) occurring under the lowest stress (50 kPa) and the lowest (7.37%) under the highest stress (200 kPa). However, as soon as TiO_2 is introduced at just 0.5%, the swelling percentage drops dramatically to nearly 0% for all stress levels and remains constant with further increases in nano-TiO_2 content (1% and 1.5%).

The near-complete elimination of swelling at only 0.5% TiO_2 indicates effect in which nanoparticles effectively occupy the critical micro- and nano-voids that govern water adsorption and expansion.

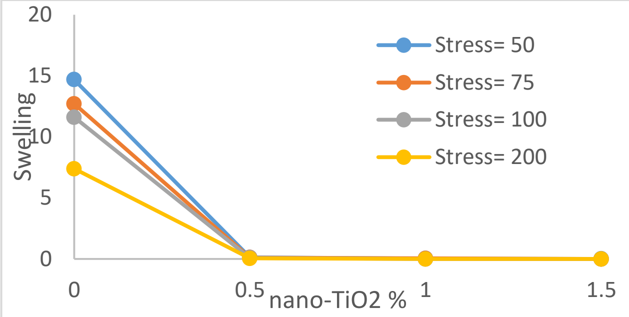

Figure 3: Swelling (%) with different percentages of TiO_2 at stresses (50, 75, 100, 200 kPa)

Figure 4 presents the effect of TiO_2 on the void ratio of expansive soil. The untreated soil exhibits the highest void ratio across all pressure levels. The addition of 0.5% TiO_2 results in a noticeable reduction in the void ratio, with further decreases observed at 1% and 1.5% dosages. The most significant reduction in void ratio occurs at the lowest dosage (0.5%), suggesting that TiO_2 achieves effective stabilization even at minimal concentrations. That indicating a loose structure with a high proportion of interconnected micro- and macro-pores. The introduction of TiO_2 nanoparticles causes a distinct reduction in void ratio, demonstrating the densification of the soil matrix. This reduction becomes evident even at the lowest dosage (0.5%)

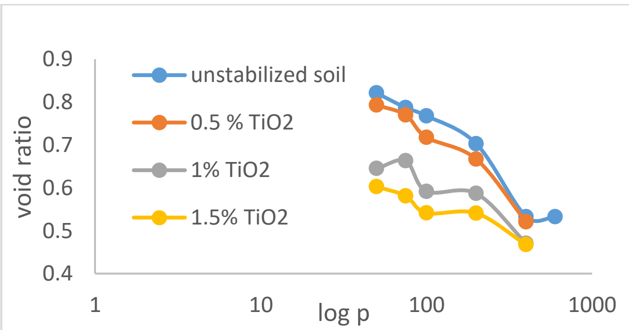

Figure 4: e-log p graphs at various percentages of nano-TiO_2

Tables (5-9) clearly demonstrate the significant influence of nano-TiO_2 content on both the swelling percent and swelling pressure of expansive soil under different applied stress conditions. The results demonstrate a significant reduction in both swelling percent and swelling pressure of expansive soil with the addition of nano-TiO_2. Under all applied stress levels (50, 75, 100, and 200 kPa), the swelling percent decreased markedly as the nano-TiO_2 content increased.

At 50 kPa, the swelling percent dropped from 14.69% with no additive to 0.0067% at 1.5% TiO_2, representing a 99.95% reduction. Similar trends were observed at 75 kPa and 100 kPa, where the swelling percent was completely eliminated (100% reduction) at TiO_2 contents of 1.5% and 1.0% or higher, respectively. At 200 kPa, the initial swelling percent of 7.38% was also fully eliminated with the addition of 1.0% or more TiO_2.

Regarding swelling pressure, the addition of nano-TiO_2 led to a substantial decrease from an initial value of 320 kPa to 300 kPa, 180 kPa, and 62 kPa for 0.5%, 1.0%, and 1.5% TiO_2, respectively. This corresponds to a maximum pressure reduction of 81% at 1.5% TiO_2. These findings confirm that nano-TiO_2 is highly effective in significantly reducing the swelling behavior of expansive soils, with the most pronounced improvements observed at contents of 1.0% and above.

The experimental findings clearly indicate that the incorporation of nano-TiO_2 significantly enhances the performance of expansive soils by reducing both swelling percent and swelling pressure. Even at low concentrations, nano-TiO_2 demonstrated a remarkable ability to limit soil expansion, with complete elimination of swelling achieved at 1.0–1.5% content under various stress levels. Furthermore, a notable decrease in swelling pressure was observed, reaching a maximum reduction of 81% at 1.5% TiO_2.

These results highlight the potential of nano-TiO_2 as an effective stabilizing agent for expansive soils, offering a promising solution for improving the stability and durability of geotechnical structures in problematic soil conditions.

Because nano-TiO_2 enhances soil microstructure by filling pores, promoting flocculation, and forming stable bonds with clay minerals, it reduces swelling and compressibility thereby increasing the soil's strength, density, and stability under loading.

Table 5. Effect of TiO_2 content on the swelling percent of expansive soil (Stress =50 kPa)

TiO_2 (%)	Swelling percent (%)	Percentages of reduction of a swell percent (%)
0	14.68781	0
0.5	0.128733143	99.12
1	0.033556638	99.77
1.5	0.006743341	99.95

Table 6. Effect of TiO_2 content on the swelling percent of expansive soil (Stress =75 kPa)

TiO_2 (%)	Swelling percent (%)	Percentages of reduction of a swell percent (%)
0	12.70116	0
0.5	0.115630182	99.1
1	0.045399099	99.6
1.5	0	100

Table 7. Effect of TiO_2 content on the swelling percent of expansive soil (Stress =100 kPa)

TiO_2 (%)	Swelling percent (%)	Percentages of reduction of a swell percent (%)
0	11.60118	0
0.5	0.083126844	99.3
1	0	100
1.5	0	100

Table 8. Effect of TiO_2 content on the swelling percent of expansive soil (Stress =200 kPa)

TiO_2 (%)	Swelling percent (%)	Percentages of reduction of a swell percent (%)
0	7.379354	0
0.5	0.049719983	99.33
1	0	100
1.5	0	100

Table 9. Effect of TiO_2 content on the swelling pressure of expansive soil

TiO_2 (%)	Swelling pressure (kPa)	Percentages of reduction of a swell pressure (%)
0	320	0
0.5	300	7
1	180	44
1.5	62	81

6. Conclusion

The present research investigated The swelling behavior of expansive soil without and with adding TiO_2. Three percentages of TiO2 used in this study (0.5%, 1% and 1.5%). The following conclusions may be drawn:

- The addition of TiO_2 significantly reduces the swelling of TiO_2 stabilized material regardless of the applied stress level. A minimal amount of TiO_2 (0.5%) is sufficient to eliminate swelling completely. This suggests that TiO_2 plays a crucial role in enhancing the dimensional stability of the material by preventing moisture uptake or expansion under mechanical stress.
- For a fixed TiO_2 content, an increase in the applied vertical stress results in a corresponding decrease in the swelling percentage.
- Even at low TiO_2 contents, its influence becomes more pronounced under higher stress conditions.
- The decrease in void ratio with increasing TiO_2 content suggests an enhancement in soil structure and overall stability. This indicates that TiO_2 contributes to improved interparticle bonding and a reduction in pore spaces, thereby decreasing compressibility and increasing the soil's resistance to deformation under applied loads.
- The swelling pressures decreased with increasing TiO_2 contents.

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