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Application of Nano-Titanium Dioxide to Collapsible Gypseous Soils for Stabilization

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Abstract

Nano titanium dioxide is a soil chemical additive that can act as a cementing agent and water barrier. This research aims to investigate how different percentages of NTD affect the collapsibility and severity of natural sandy soils with gypsum contents of 35, 50, and 60%, taken from three other locations in the Salah Al-Deen government. Single- and double-oedometer tests were conducted to investigate the collapsibility of gypseous soils stabilized with NTD and to compare them with untreated soil samples. All test results for both single- and double-oedometer tests showed a significant effect of NTD on decreasing Cp values, with varying percentages and, hence, a transformation in the degree of severity across the three tested soils at NTD percentages of 0.1, 0.3, and 0.5%. These findings suggest that even trace amounts of NTD could be a promising agent for stabilizing collapsible gypseous soils in civil engineering projects. This could lead to more stable and reliable ground support in areas with prevalent soil types. Advances in the application of nano titanium dioxide are opening new avenues for enhancing soil stabilization techniques and ensuring the longevity of engineering structures.

Keywords: Collapsible soil, Scanning electron microscope, Gypseous soils, Nano stabilization, Nano titanium dioxide.

1. Introduction

The soils in the unsaturated state that undergo a severe reordering of particles associated with significant losses of volume upon wetting without or with extra loading are called collapsible soils [1]. Bonding material and pore morphology are proposed as the main features that further affect the collapse behavior [2]. When wetted, collapsible soils exhibit a metastable structure that undergoes a significant volume decrease and collapse. Gypseous soils are usually classified as collapsing soil because gypsum provides apparent cementation in the dry state. However, the presence of water still leads to dissolution and softening, generally causing severe structural collapse [3], [4].

Soluble salts are present in natural soils and aggregates in varying amounts across most of the world [5]. One of these soluble salts that damages earthen buildings and pavement is gypsum. Gypsum is among the most common salts in Iraq [6]. Gypsum, CaSO4 · 2H2O, is classified as a hydrated calcium sulphate and occurs in many other forms, including Bassanite, $CaSO_4$. ½H_2O and Anhydrite $CaSO_4$ [7]. Pure gypsum contains 46.6% sulphur trioxide SO_3, 20.9% combined water H_2O, and 32.5% CaO [8]. Gypsum specific gravity is 2.32, which is a relatively low value that significantly influences the mechanical and physical properties of soils containing large quantities of gypsum [9]. Saleam [10] stated that gypsum might be found in numerous forms, such as thick beds that are likely to include anhydrite; thinner bedded gypsum; and crystals in surface layers, sometimes crust or recrystallized from evaporated groundwater and gypsum powder, which are distributed in the soil mass or buried layers, and are possibly associated with terrace deposits. In the soil structure, gypsum acts as a cementing material when the soil is dry. However, gypseous soils can dissolve and soften due to water infiltration from rainfall, a rise in the water table, leaks, and other causes. This may lead to damage or even collapse of structures built on this type of soil, because structural elements cannot accommodate unexpected deformation through reorganization of internal stresses or forces [11]. Since gypsum affords a cohesive result, gypseous soil is characteristically stiff when dry. Due to the solubility of gypsum, it significantly increases in compressibility and decreases in strength upon contact with water [12]. Due to the gypseous soil's collapsibility, which causes significant volumetric compression when wet, these soils are stable when unsaturated [13]. When collapsible soils are naturally moist, they may withstand large loads with minimal compression or distortion. However, when wetting occurs, a significant decrease in the volume of the gypseous soil also occurs [14]. The cementing agent between soil particles is affected by variations in moisture content and gypsum dissolution, which can lead to sudden settlement and collapse [15].

The issues that Iraqi soils contain great quantities of gypsum roughly 31% of the Iraqi area, can be summed up as follows: substantial strength losses and an abrupt rise in compressibility whilst wet, ongoing collapse and deformation following leaching as a result of the movement of the water, and the sink holes presence in the soil consequently of the dissolution of gypsum [16]. Based on the oedometer collapse test results, Tables 1 and 2 present the classification of collapsible soil by severity.

Table 1. Collapsible soil severity [17].

Cp %	Severity
0.0	No trouble
0.1 to 2.0	Slight trouble
2.1 to 6.0	Moderate trouble
6.1 to 10.0	Moderately severe trouble
> 10.0	Severe trouble

Table 2. Collapsible soil severity [18].

Cp %	Severity
< 1	**No trouble**
1 to 5	**Moderate trouble**
5 to 10	**Trouble**
10 to 20	**Severe trouble**
> 20	**Very severe trouble**

Gypsum content in the soil affects the collapse potential: higher gypsum content is associated with greater collapse potential. The *Cp* under a stress of 200 kN/m2 increases with increasing gypsum content [18]. Fattah et al. [19] reported that as gypsum content rises from 14.8% to 66% and void ratio increases, the Cp value in single- and double-oedometer tests increases significantly. Moreover, the breaking of grain bonds caused by gypsum dissolution in wet, sandy gypseous soil leads to the collapse of the soil's metastable structure [20]-[22].

Construction sites on low-quality ground are increasing, prompting the introduction of several novel methods to stabilize unstable soil. One strategy involves utilizing nanoparticles to enhance soil index properties and strength to attain the desired stability. Nanomaterials like SiO_2, TiO_2, and Al_2O_3 can stabilize soil [23].

The principal distinction between a nanomaterial and a larger-scale material is that the nanomaterial's greater surface area enables extensive chemical reactivity [24]. Even a small amount of nanoparticles may have extraordinary effects on the soil's engineering features. The study found that nano-particles influence soil's permeability, strength, indices, and resistance properties [25]. Nanomaterials' impacts on soils' geotechnical properties have attracted considerable attention and warrant designation [26]. Soils improved with nanomaterials could enable a novel, intelligent, eco- and environmentally friendly construction material [27].

Khalaf et al. [28] concluded that the nanomaterials exhibit distinct characteristics, including smaller sizes and high specific surface areas, and thus interact strongly with particles in the soil matrix. A small amount of nano-materials can significantly affect soil geotechnical properties (enhance the properties of the soil) and the effect of the various types of nano-materials based on the particle category, proportion, and soil type. A reasonable reduction in the collapse potential value reached 75% at the double oedometer test was noticed by Al-Obaidi et al. [29] by increasing the (nano silica fume) additive percentage to 3% in a gypseous sandy soil with 62% gypsum content. Additionally, the outcomes reported by Hayal et al. [30] showed that increasing the nanocarbon percentage to 0.4% in sandy gypseous soil with 31% gypsum content reduced the *Cp* value from 3.6 to 1.442. The value of the collapse potential decreased by 60%, indicating a drop in problem risk from moderate to slight. The same result was obtained by Karkush et al. [31] when mixing a sandy gypseous soil with 54% gypsum and 4% nano-clay, in which the severity of soil collapse was reduced from severe to moderate.

The element that is the ninth most common in the crust of the planet is titanium. The transition metal oxide family includes nano titanium dioxide. At 25°C, its relative density is 4.26 g/cm³. Nano titanium dioxide is a white, odorless, and fireproof powder. Water, dilute acids, and common organic solvents do not dissolve nanotitanium dioxide. Nano titanium dioxide can be dissolved in hydrofluoric or concentrated sulfuric acid at high temperatures [32]. Roy [33] and Chenthakunta et al. [34] demonstrated that nano titanium dioxide is non-toxic and non-flammable, making it a solid transition metal oxide that is comparatively abundant and environmentally friendly. High chemical stability, heat resistance, and resistance to oxidation and corrosion characterize it. Three crystalline natural forms of nano titanium dioxide are occurring: rutile, brookite, and anatase. The most stable phase is rutile, although the metastable phases anatase and brookite can transform into rutile upon heating.

Research on the use of nano titanium dioxide as a soil alteration is a popular topic, drawing the interest of numerous researchers, as this additive is widely applied in textiles, construction materials, and biomedicine. Research in civil engineering construction primarily focuses on the use of nano titanium dioxide as an additive in cement-based materials. Concrete's acid resistance and bending fatigue can be enhanced by adding a suitable amount of nano titanium dioxide [35]. Due to its chemical composition and large specific surface area, nano titanium dioxide is used as an additive to address soil low shear strength and high compressibility from a geotechnical perspective by modifying soil properties [36]. Large-scale manufacture is possible due to the low cost of producing nano titanium dioxide, which is expected to be an affordable replacement for traditional additives [37], [38]. While nano titanium dioxide can somewhat reduce the plasticity index of clayey silt treated with it, it can significantly raise the plastic and liquid limits of the silt. Related to untreated samples, the standard compaction test indicates that optimal water content rises and the maximum dry density declines. The extremely small nano titanium dioxide particle size, 0–100 nm, may be the cause of its influence on clayey soil's physical performance [37]

Due to the limited research on nano titanium dioxide (NTD) as a stabilizer for gypseous soils, this study aims to quantitatively determine the effect of varying NTD percentages on collapse potential. Furthermore, it seeks to identify an economically optimal dosage that can be applied in practice to mitigate the severe risks associated with these problematic soils. To achieve this, three kinds of gypseous soils from Iraq were subjected to a comprehensive testing program, including single- and double-oedometer tests, to provide reliable data for the design of cost-effective and stable foundations in gypseous soil regions.

2. Methodology

Physical, chemical, and collapse tests were conducted to observe the behavior of three collapsible gypseous soils and determine the effect of adding NTD. For each soil-test combination, two sets of soil samples were arranged under the same conditions, with the exact additive amounts, to gain middling test results and improve accuracy.

2.1 Chemical and Physical Tests

The physical tests, including soil classification, were conducted in accordance with standards to determine soil indices such as moisture content, Atterberg Limits (LL, PL, and PI), Gs, and sieve analysis. Because the soils contain gypsum, kerosene was used instead of distilled water in Gs tests to avoid dissolution of gypsum during testing [15], [39]. A scanning electron microscope FE-SEM was used to explore the micro variations in the soil particle structure with NTD before and after soaking. Small fragments of gypseous soil (approximately 3–5 mm) were gently air-dried at room temperature to prevent gypsum dehydration. The dried samples were mounted on aluminum stubs using conductive carbon tape and coated with a thin carbon layer (≈5–10 nm) to prevent charging. The specimens were examined using a scanning electron microscope at accelerating voltages of 5-15 kV and a working distance of 8–12 mm to characterize surface morphology and microstructural features.

A standard series of tests evaluated the chemical properties of the tested soils, and two techniques were utilized to quantify the amount of gypsum in the soils:

A- Al-Mufty and Nashat technique

Al-Mufty and Nashat [16] presented this approach.to determine the gypsum contents. It relies on heating the gypsum salt between the soil particles under test. Expulsion of the water from the particles of the gypseous soil is made by putting the tested soil samples in an oven set to 45 degrees Celsius for a few days until the tested soil's weight stays consistent., indicating that the gypsum starts to lose the crystallization water), then heating the gypsum by putting the same soil samples in the oven at a specific temperature of 105ºC till the weight of the tested soil samples stabilized at the same amount which means all the hydration water is lost and the sample becomes anhydrite. After that, according to (1), the amount of gypsum is calculated:

$$X = \frac{W_{45^\circ C} - W_{105^\circ C}}{W_{45^\circ C}} \times 4.778 \times 100 \quad (1)$$

Where:

X = Content of gypsum by weight, %,

$W_{45^\circ C}$ = Weight of the tested sample at 45 °C,

$W_{105^\circ C}$= The tested sample's weight at 105 °C, and

4.778 = Inverse ratio of hydration water molecular weight to gypsum molecular weight.

B- The approximate technique

This technique was applied to determine the gypsum content in the examined soil samples in accordance with the British Standard by multiplying the total sulphate (SO3) value by 2.15, as shown in (2).

$$X = SO_3 \times 2.15 \quad (2)$$

Where:

X = The content of gypsum %,

SO_3 = The total sulphate content, and

2.15 = The inverse proportion of molecular hydration of water weight to molecular weight of gypsum.

2.2 Single Oedometer Test

Collapse tests were carried out to investigate the behavior of the tested soils stabilized by nano titanium dioxide NTD at 0.1, 0.3, and 0.5% and contrasted with the untreated soil samples, as shown in Fig. 1. To compute the collapsibility of the soils at the single oedometer test, the *Cp* was determined according to the (ASTM D5333) specification at 200 kPa of vertical stress as illustrated in Fig. 2 for untreated soil samples and treated soil samples with different percentages of nano NTD. This test involves testing the soil with a sample positioned in the oedometer cell at its natural water content and a relative density of 50% (unsaturated conditions), and applying loads gradually until the pressure reaches 200 kPa. After the loading process is complete, water is added and allowed to stand for 24 hours, with any volume changes measured. Subsequently, the test is conducted at the specified pressure. The *Cp* is described as (3) [40].

$$C_p = \frac{\Delta e}{e_0} \times 100 = \frac{\Delta H}{H_0} \times 100 \quad (3)$$

Where:

C_p = Collapse potential,

Δe = Changes the ratio of voids after wetting,

e_o = Natural void ratio,

ΔH = Change in height upon wetting and

H_o = Initial height.

Figure 1. Collapse test for gypseous soil samples under test.

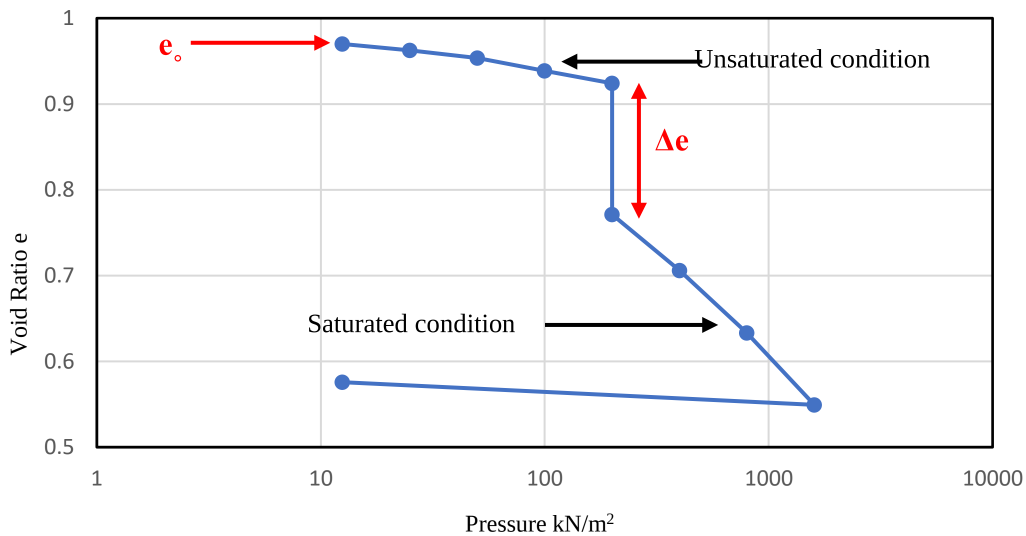

Figure 2. Typical result of a single oedometer test.

2.3 Double Oedometer Test

This kind of test relies on utilizing two similar oedometer samples from the identical tested untreated and treated soil samples S1, S2, and S3, with different percentages of NTD 0.1%, 0.3%, and 0.5% by weight and a relative density of 50%; the first one is tested at natural water content (unsaturated condition) from the beginning till the end of the test, and the second one is tested under saturated condition after soaking the soil samples from the beginning to the end of the test with water. The difference between the two sample results illustrated the soil's collapse potential under any stress. The collapse potential percentage is computed in accordance with ASTM D5333 when using the oedometer cell under constant temperature and humidity. The test output and the process are similar to those of a single oedometer test. Fig. 3 presents typical results from double oedometer tests.

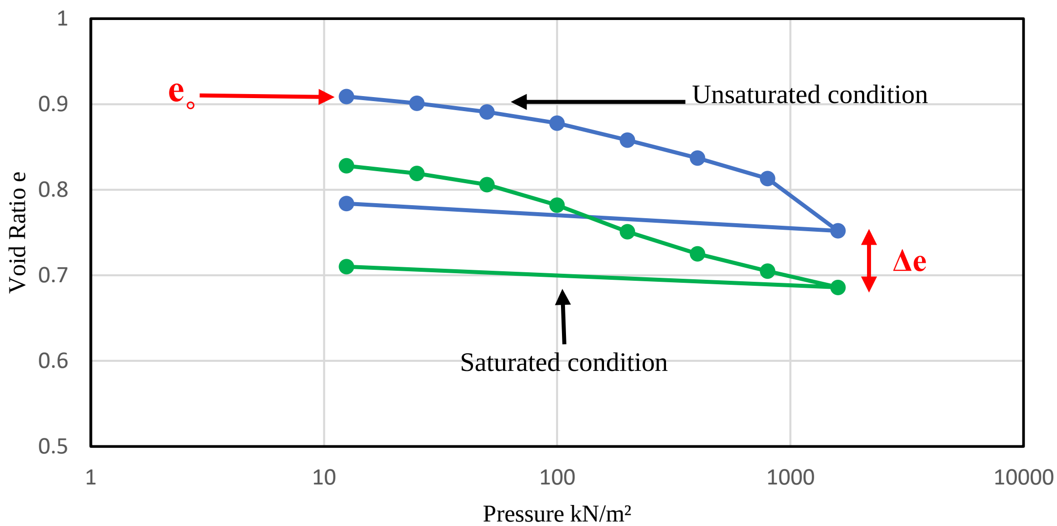

Figure 3. Typical result of the double oedometer test.

3. Materials

3.1 Soils

The tested soils employed in this study are natural sandy gypseous soils taken from three locations in the city of Tikrit in Salah Al-Deen government, north of the city of Baghdad (Iraq's capital city), with various gypsum contents, as shown in Fig. 4. The specimens were extracted at a depth of 1.5-2.5 m below the surface. Soil samples were gathered by an excavator and stored in sturdy nylon bags until testing began. The distribution curves of the particle size of the gypseous soil samples are represented in Fig. 5. At the same time, the particle size analysis of the examined gypseous soils is summarized in Table 3 following [41], [42] specifications. Utilizing the USCS, S1 is categorized as SP-SM, and S2 is categorized as SW-SM. In contrast, S3 is classified as SP gypseous soils.

Figure 4. The intake regions from the three locations in Tikrit City, Iraq.

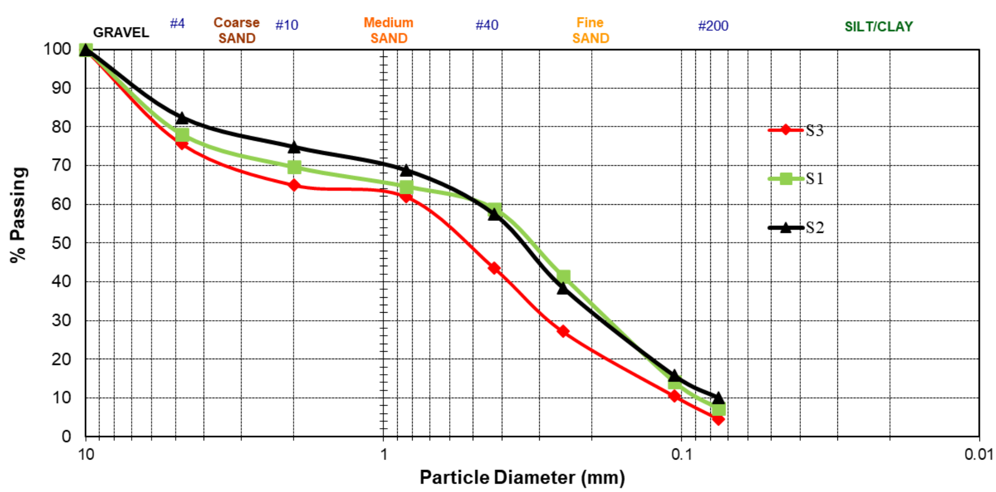

Figure 5. Particle size distribution curves of the gypseous soils.

Table 3. Classification and size analysis of the tested soil.

SOILS	GRAVEL %	SAND %	FINES %	CLASSIFICATION*
SOIL 1	22.0	70.8	7.2	SP-SM
SOIL 2	17.6	72.4	10.0	SW-SM
SOIL 3	24.4	71.0	4.6	SP

* USCS: Unified Soil Classification System.

Table 4 presents the Atterberg limits (PI, LL, and PL) reported in [43]. Based on particle-size analysis, the three gypseous soils had no PL. The Gs values of the tested gypseous soils were determined according to [39]. The results show that the specific gravity values for the untreated tested soils Soil 1, Soil 2, and Soil 3 are 2.62, 2.59, and 2.55, respectively. Specific gravity tests show a decrease in Gs values for gypseous soils with increasing gypsum content. The values of the Gs for the three tested gypseous soils are less than the usual limits of 2.65-2.67 (Bowles, [44]), especially in Soil 2 and Soil 3 with higher gypsum contents because of the effect of the low specific gravity of the gypsum 2.32 [39]. The tested soils have a low natural moisture content [45]. This relates to the soil sampling season, which occurred in hot, dry weather and at a distance from the groundwater table. The minimum and maximum dry unit weights (ASTM D 4254 and ASTM D 4253) and optimum moisture contents (ASTM D 698) of the tested gypseous soils are listed in Table 4, too.

Table 4. The tested soil's physical properties.

Tested Soils	Atterberg limits			Specific gravity Gs	Natural water content W%	Optimum moisture content O.M.C%	Minimum dry unit weight γdry.min kN/m³	Maximum dry unit weight γdry.max kN/m³
	LL%	PL%	PI%					
Soil 1	21	NA	21	2.62	1.3	13	12.21	16.19
Soil 2	23	NA	23	2.59	1.8	12	11.76	15.37
Soil 3	20	NA	20	2.55	2.0	11	11.13	16.43

Table 5 illustrates the chemical properties of the tested soils. Different gypsum contents were observed because the tested soils were taken from different locations. The tested gypseous soil S1 has the lowest gypsum content, about 34%, while S2 and S3 have higher gypsum contents, approximately 50% and 60%, respectively.

Table 5. The tested soil's chemical characteristics.

Characteristic	Soil 1	Soil 2	Soil 3	Specification
Gypsum content %	34.82	49.98	59.63	[16]
	34.19	50.51	60.17	[46]
Total sulphate content SO_3 %	15.90	23.49	27.99	[46]
pH value	8.10	8.17	8.21	[46]

3.2 Nano Titanium Dioxide NTD

Tests were conducted to examine the influence of using nano-material in stabilizing gypseous soils. The nano titanium dioxide used in this research was provided by the U.S. advanced nanomaterials company, US Research Nanomaterials, Inc., and its main characteristics are presented in Table 6. NTD is a low-density, lightweight white powder, as illustrated in Fig. 6. Fig. 7 shows FE-SEM images of the NTD used in the study. The FE-SEM image of NTD indicates a nearly spherical form with a typical particle size of 37-44 nm.

Table 6. Properties of NTD.

Property	Value
Appearance	White
Formulation	TiO_2
Purity %	99
Density (g/cm³)	4.250
Particle size (nm)	30-50
Category	Rutile

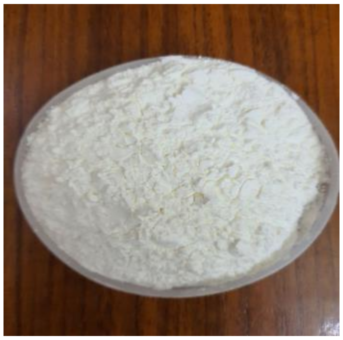

Figure 6. Nano Titanium Dioxide.

4. Result and Discussion

4.1 Single Oedometer Test

The results of the single oedometer test for untreated and treated soil samples with different percentages of NTD for S1, S2, and S3 are illustrated in Figs. 8, 9, and 10, respectively. The results demonstrate that with increasing percentages of nano titanium dioxide NTD, the void ratios, hence the collapse potential values *Cp,* as Equation 3 states, decrease for the three tested gypseous soils in varying proportions for all additive percentages.

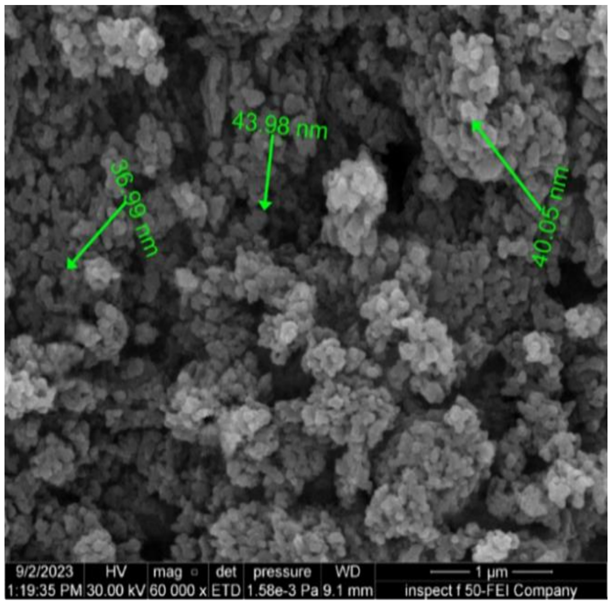

Figure 7. FE-SEM result for NTD.

The untreated soil sample exhibited a high collapse potential, Cp 7.77%,8.45% and 12.24% for S1, S2, and S3, respectively, as shown in Fig. 11 and Table 7, which may relate to the gypsum's dissolution, the breaking of the connections between soil granules, and the reorientation of particles. The void ratio, and hence the collapse potential, of the three tested gypseous soils decreased with increasing additive material NTD percentage, with a pronounced decrease observed for the treated soil at 0.3%. Then, a slight decline happened in the *Cp* values when the percentage of NTD became 0.5%, which emphasizes that the increase in the rate of the improvement of material NTD does not meaningfully affect the mechanical behavior of the tested gypseous soils. This improvement in the collapse potential *Cp* values results from filling the voids between soil particles with NTD nanoparticles, which act as a filler. In addition, it imparts a waterproofing layer to the tested gypseous soil particles and strengthens the soil structure against collapse when water is added.

The reduction in Cp values results in a shift in the severity of gypseous soils S1 and S2 from moderately severe to slight [17] and from trouble to no problem [18]. Although the gypseous soil sample S3 initially exhibited severe severity, the soil mutation subsequently changed to slight [17]. According to Jennings and Knight [18], the classification of the severity of the collapsed soil S3 based on single oedometer test results indicated that the soil changed from severe trouble to moderate trouble.

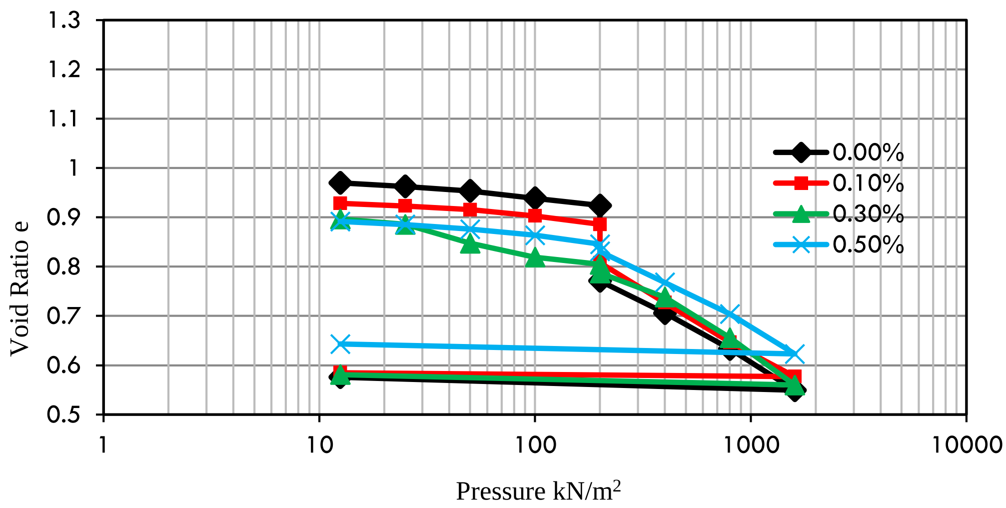

Figure 8. Single oedometer test results for untreated and treated S1 soil.

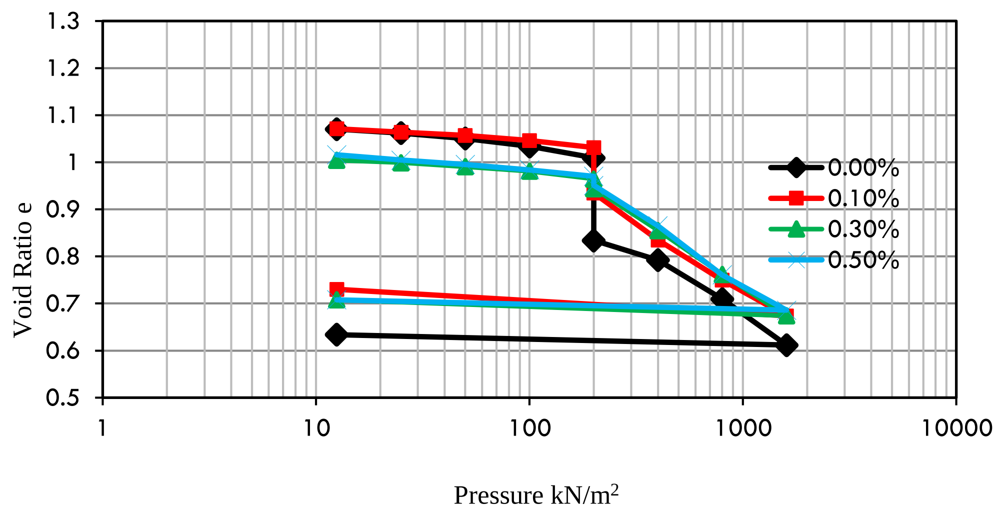

Figure 9. Single oedometer test results for untreated and treated S2 soil.

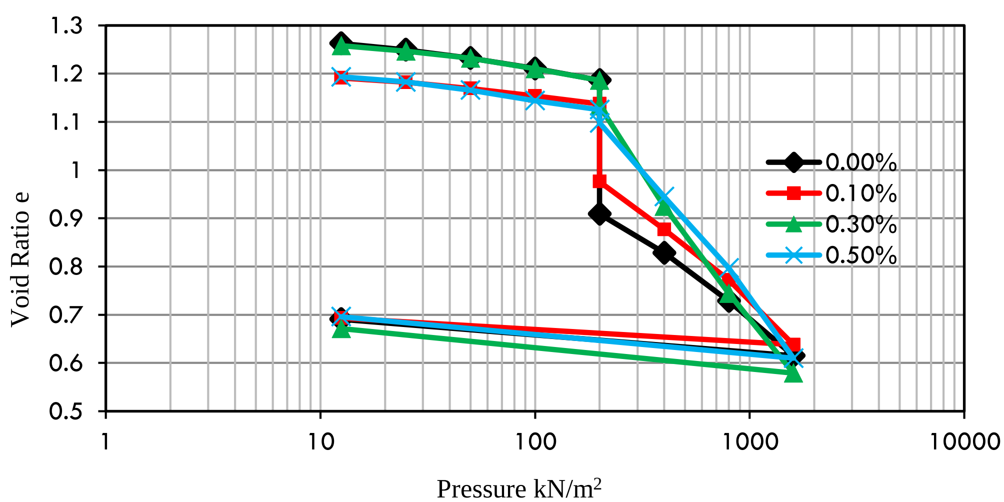

Figure 10. Single oedometer test results for untreated and treated S3 soil.

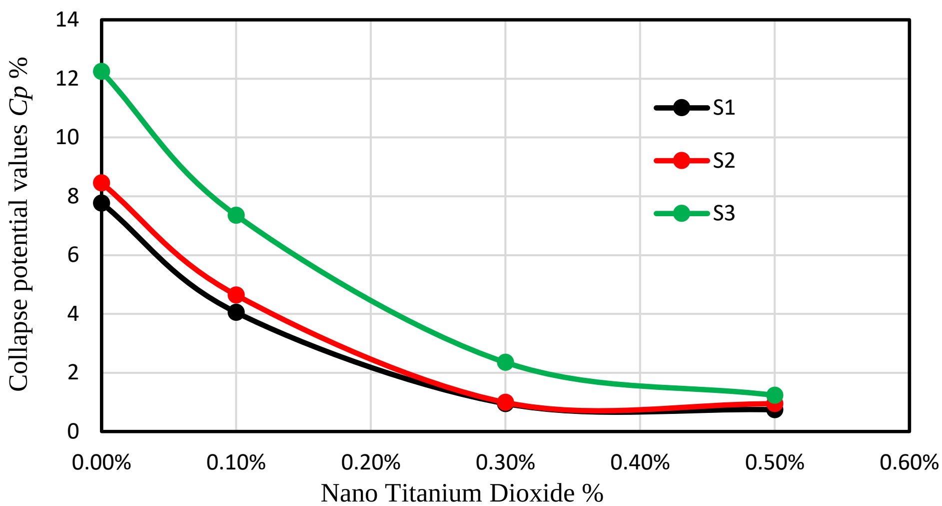

Figure 11. Collapse potential *Cp* values versus different percentages of NTD.

Table 7. Enhancement of NTD percentages on collapse potential *Cp* values for untreated and treated soils.

Soil	*Cp* %				Degree of severity	
	Untreated soil	0.1% NTD	0.3% NTD	0.5% NTD	ASTMD5333, [17]	Jennings and Knight,[18]
S1	7.77	4.05	0.95	0.74	Moderately sever-slight	Trouble-no problem
S2	8.45	4.64	0.998	0.943	Moderately sever-slight	Trouble-no problem
S3	12.24	7.35	2.35	1.23	Sever-slight	Severe trouble-moderate trouble

These significant results lead to more robust conclusions than those of Hayal et al. [30], who concluded that a 0.4% increase in the nanocarbon portion of sandy gypseous soil with 31% gypsum content results in a decline in *Cp* from 3.6 to 1.442. The value of the collapse potential decreased by 60%, indicating a drop in problem risk from moderate to slight. Moreover, the results obtained in this study, with lower percentages of NTD, were better than those reported by Karkush et al. [31] for a sandy gypseous soil mixed with 54% gypsum and 4% nano clay, in which the soil's Cp was reduced from severe to moderate.

The mechanism of collapsibility can be illustrated by the first collapse of gypseous soil, in which gypsum dissolves when the soil becomes wet, thereby breaking grain connections [21]. Upon wetting, weakened cementation bonds cause the initially slack structure to collapse, often resulting in disastrous settlement [47], [48]. Gypsum can dissolve, reducing its volume. In addition, leaching may occur within cracks and fissures within the gypsum body due to fluctuations in groundwater levels and surface water infiltration [49].

4.2 Double Oedometer Test

According to ASTM D5333 [17], for untreated and treated soil samples with NTDs of 0.1, 0.3, and 0.5%, the values of the collapse potential *Cp* were determined at the same pressure by applying the double oedometer test. This test compares two samples of the same soil with the same properties and additive percentages (for treated samples), but one remains dry, and the other is kept saturated throughout the test. The results for treated soil samples with different percentages of NTD and for untreated soil samples for the gypseous soils are illustrated in Figs. 12, 13, and 14, respectively.

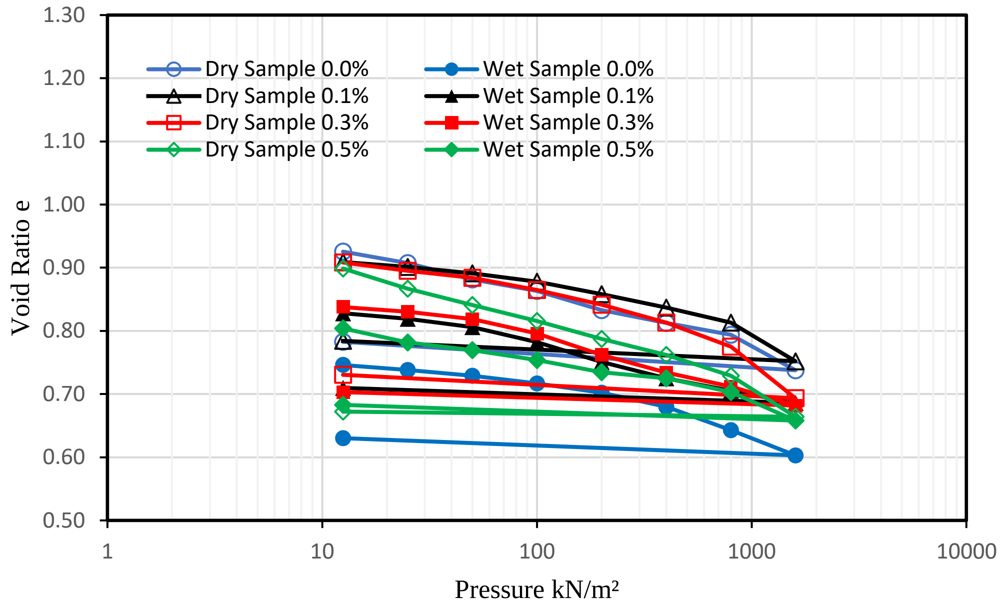

Figure 12. Double oedometer test results for the untreated and treated S1 soil.

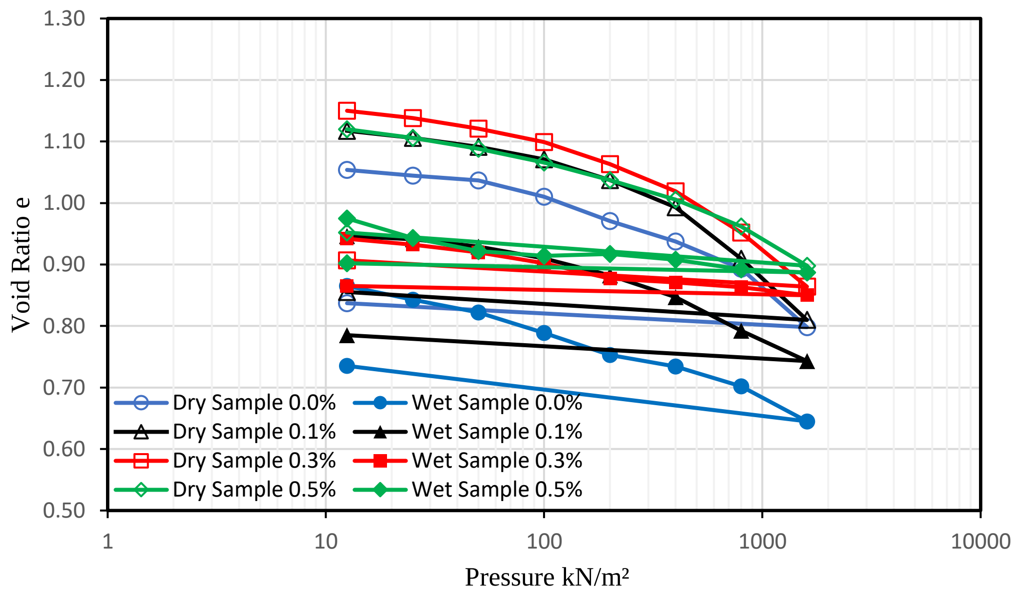

Figure 13. Double oedometer test results for the untreated and treated S2 soil.

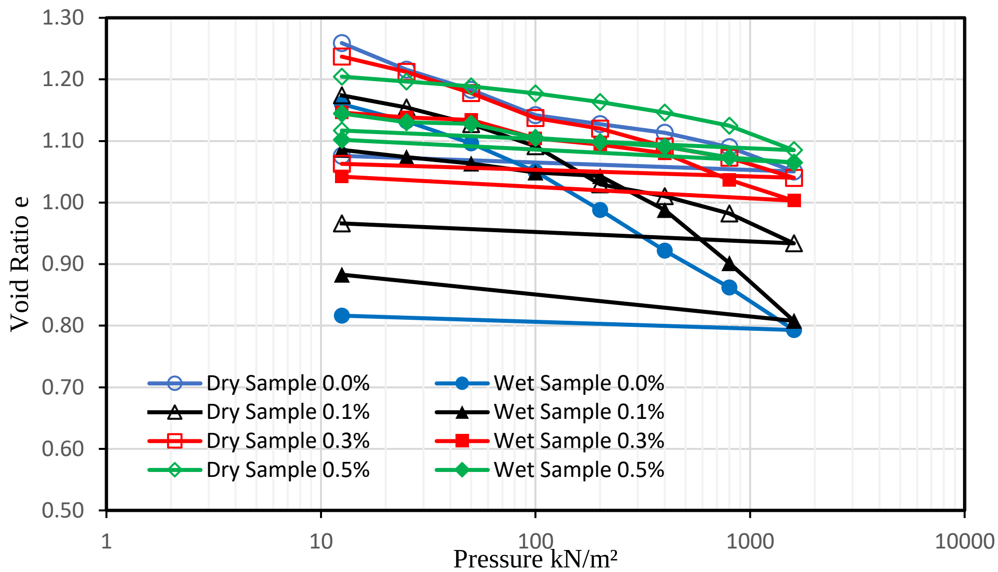

Figure 14. Double oedometer test results for the untreated and treated S3 soil.

Figs. 12 to 14 demonstrate the result of adding NTD at percentages of 0.1%, 0.3%, and 0.5% by weight. All test results showed a decrease in Cp values for the three soils as the amount of NTD increased. For the tested soil S1, the collapse potential value *Cp* decreased by about 95.49%, and for the S2 gypseous soil by 93.03%. In comparison, S3 appears to have a 92.03% reduction in the *Cp* value when adding the highest addition rate o.5% of nano titanium dioxide NTD, which serves as a binding agent for the soil's particles, and in addition, coating and preventing them from dissolving. Similarly, a reasonable reduction in the collapse potential value, reaching 75%, was observed by Al-Obaidi et al. [29] by increasing the nano silica fume additive to 3% in a gypseous sandy soil with 62% gypsum content.

Figs. 15 and Table 8 show that the untreated soil samples S1, S2, and S3 had a high collapse potential of 7.01%, 7.45%, and 11.377%, respectively. The reason for this is the collapse of soils, which are often characterized by an open, loose structure surrounded by cementing agents, in this case, gypsum. Upon wetting, the structure collapses when the binders reach a point at which they can no longer withstand deformational forces.

The decrease in the values of *Cp* for the tested soil samples S1 and S2 as the NTD increased primarily when adding 0.3 and 0.5% of NTD leads to the same results in transferring the severity of the soil from moderately severe to slight [17] and from trouble to no problem [18] for double oedometer test results. Depending on the *Cp* value of the gypseous soil sample S3, the double oedometer test results indicate a change from severe to slight [17], whereas, according to Jennings & Knight [18], the classification of the severity of the collapse soil S3 transmission changes from severe trouble to no problem.

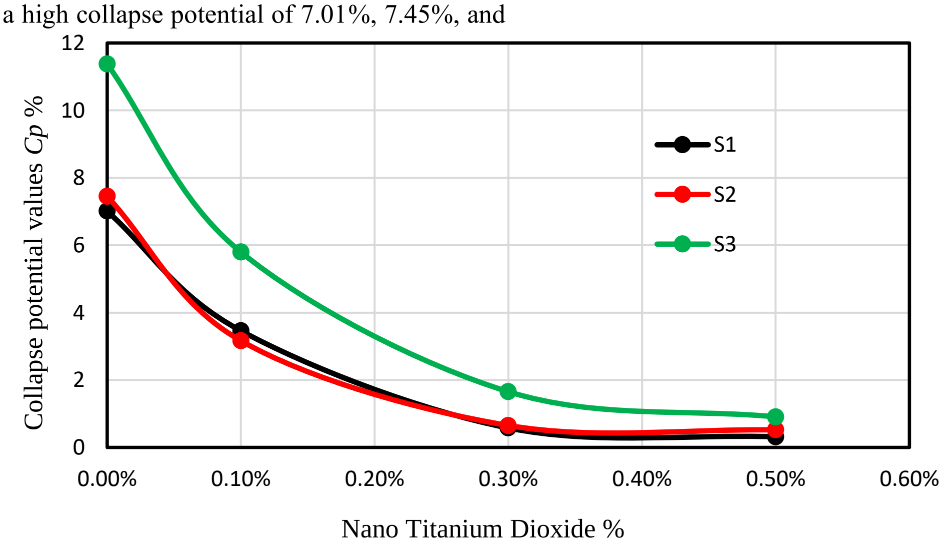

Figure 15. Collapse potential values *Cp* versus different percentages of NTD.

Table 8. Enhancement of NTD percentages at *Cp* values for untreated and treated soils.

Soil	*Cp* %				Degree of severity	
	Untreated soil	0.1% NTD	0.3% NTD	0.5% NTD	ASTMD5333 [17]	Jennings and Knight [18]
S1	7.01	3.46	0.577	0.316	Moderately sever-slight	Trouble-no problem
S2	7.45	3.165	0.651	0.519	Moderately sever-slight	Trouble-no problem
S3	11.377	5.796	1.654	0.907	Sever-slight	Severe trouble-no problem

The threshold water content, which varies with the applied vertical stress and the soil's initial water content, marks the onset of significant collapse. The soil's bonding strength is no longer sufficient to sustain it when its water content exceeds a certain threshold [3].

For the same vertical stress level, the collapse potential values produced using the single oedometer approach were comparatively higher than those obtained using the double oedometer method. The behavior makes sense given that, in the single oedometer test, all of the gypsum particle cementing bonds were maintained in the structure of the soil up until a sudden inundation occurred at the designated pressure. In this case, volumetric strain development led to significant and rapid deformations, and gypsum dissolving weakened the cementing connections [49].

Tables 9 and 10 summarize the improvement ratios of the *Cp* values for the single oedometer and double oedometer test results, respectively.

Table 9. Enhancement of NTD on ratios improvement of the *Cp* for treated soils at a single oedometer test.

Soil	Improvement ratio of collapse potential values *Cp*			
	0.0% NTD	0.1% NTD	0.3% NTD	0.5% NTD
S1	------	47.88	87.77	90.48
S2	------	45.09	88.19	88.84
S3	------	39.95	80.80	89.95

Table 10. Enhancement of NTD on ratios improvement of the Cp for treated soils at a double oedometer test.

Soil	Improvement ratio of collapse potential values *Cp*			
	0.0% NTD	0.1% NTD	0.3% NTD	0.5% NTD
S1	------	50.64	91.77	95.49
S2	------	57.52	91.26	93.03
S3	------	49.10	85.46	92.03

The nanostructure of the studied gypseous soil sample S1, treated with 0.5% nano titanium dioxide NTD in both dry and saturated states, is depicted in FE-SEM Figs. 16 and 17, respectively. Before they become saturated, gypsum particles have sharp edges. Several undissolved gypsum particles are observable in the soil matrix, indicating that cementitious compounds are forming as shells encase and bind sand particles. At the same time, nano titanium dioxide NTD performs as a filling material within the soil matrix. The results obtained are consistent with those reported by Li et al. [50], thereby confirming the reliability of the current experimental outcomes. The figures also demonstrate binding between partially dissolved gypsum crystals and sand particles in the saturated state, and the presence of noticeable voids between soil particles compared with the dry state, leading to a reduction in collapsibility.

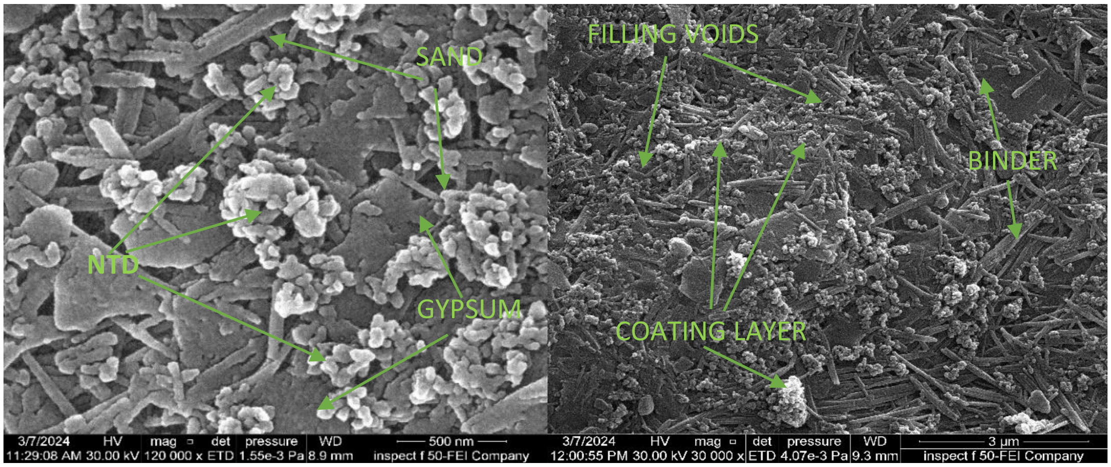

Figure 16. FE-SEM results for the S1 gypseous soil treated with 0.5% Nano Titanium Dioxide NTD in a dry state.

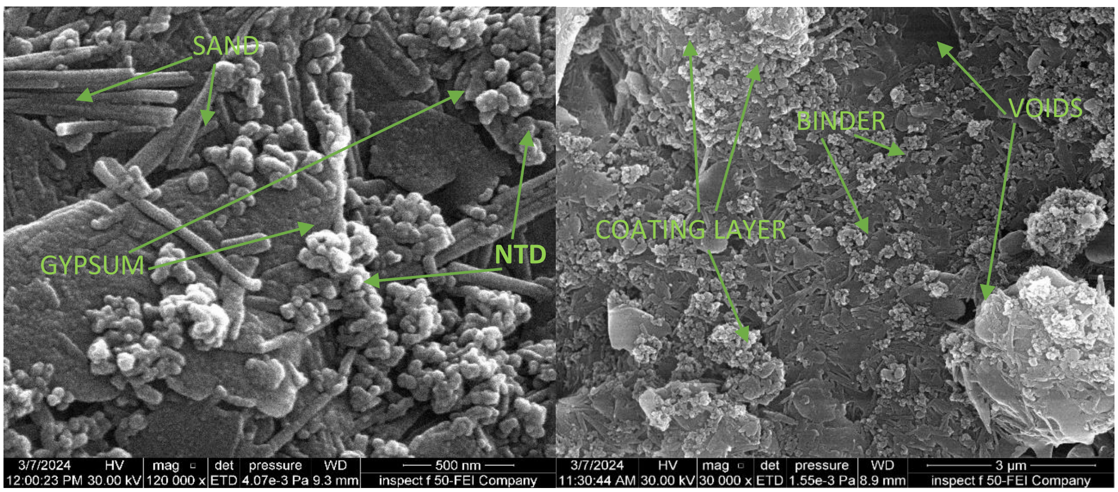

Figure 17. FE-SEM results for the S1 gypseous soil treated with 0.5% Nano Titanium Dioxide NTD in a saturated state.

5. Conclusions

This study demonstrates that nano-titanium dioxide (NTD) is a highly effective stabilizer for collapsible gypseous soils. The key practical and economic findings are as follows:

The addition of small percentages of NTD (0.1% to 0.5%) significantly reduces the collapse potential (*Cp*) of gypseous soils, transforming their severity classification from 'moderately severe' or 'severe' to 'slight' or 'no problem'. This directly translates to a reduced risk of structural damage and lower foundation design costs.

From a practical and economic standpoint, the laboratory results indicate that 0.3% NTD is the most cost-effective dosage. This percentage accounts for most of the improvement in soil stability, suggesting that higher dosages, while slightly more effective, may not be cost-effective for large-scale field applications.

The mechanism of improvement, verified by FE-SEM, shows that NTD acts as a filler, binder, and waterproofing agent, reinforcing the soil structure against water infiltration—the primary trigger for collapse.

While the unit cost of NTD may be higher than traditional stabilizers, its exceptional effectiveness at very low dosages makes the overall treatment economically viable. The potential savings from preventing catastrophic settlement and ensuring infrastructure longevity provide a strong economic case for adopting this approach in civil engineering projects on gypseous soils.

The use of nano titanium dioxide can provide more stable and reliable ground support in areas with gypseous soils, reducing the risk of collapse and improving safety. Additionally, although the material may have a higher initial cost than conventional stabilizers, its effectiveness at low dosages and potential for long-term performance improvements could make it economically feasible for field applications.

A limitation of the study is that future studies should consider the long-term stability of such material, nano titanium dioxide, and its strength characteristics.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contributions

Najwa Wasif Jassim, and Mastura Azmi are responsible for conceptualization and investigation.

Najwa Wasif Jassim and Mohammed Yousif Fattah designed the methodology,

Najwa Wasif Jassim did the data curation and wrote the first draft of the paper.

Mastura Azmi and Mohammed Yousif Fattah supervised, reviewed, and edited the final version of the writing.

All authors have read and agreed to the published version of the manuscript.

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