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Durability of Gypseous Soil Stabilized with Nano-silica under Environmental Conditions

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ABSTRACT

Gypseous soils possess unique properties that distinguish them from other soil types, particularly their increased deformation in response to environmental changes, such as wetting and drying cycles. Recently, nano-silica has been utilized as an additive to enhance the geo-technical properties of soils. This study presents a detailed analysis of nano-silica's properties and its effects on reducing dissolved salt content while improving the bonding between particles in gypseous soil with a high gypsum content of 80.4%. The durability of the treatment was evaluated by measuring the unconfined compressive strength, considering factors, such as aging, wetting-drying cycles, and freezing-thawing cycles. The tests were conducted on gypseous-soil samples before and after treatment with several ratios of nano-silica (1, 2, 3, 4, and 5%). The effects of aging were assessed at intervals of 0, 7, 14, 21, and 28 days, while the impacts of wetting-drying and freezing-thawing cycles were evaluated after 0, 1, 3, 6, 12, and 24 cycles. The results demonstrated an increase in soil cohesion with aging, ranging from 33.35% to 57.42%. Adding 1% and 2% nano-silica was insufficient to significantly enhance the geo-technical properties of gypseous soil, whereas 4% and 5% nano-silica yielded comparable improvements. However, soil cohesion decreased with an increasing number of wetting-drying and freezing-thawing cycles, ranging from 6% to 100% and from 15% to 100%, respectively.

Keywords: Gypseous soil, Leaching, Nano-silica, Durability, Problematic soil, Geo-technical properties.

INTRODUCTION

Gypseous or gypsiferous soils are those soils containing significant amounts of gypsum ($CaSO_4 \cdot 2H_2O$), which can adversely affect the stability of buildings constructed on them, particularly when exposed to wetting or soaking. Gypseous soils are widely distributed and can be found in countries, such as Russia, Spain, Australia, and Argentina. In Iraq, these soils cover approximately 20% of the country's total area, making them a significant soil type in the region. Furthermore, Iraq accounts for about 9% of the world's total gypseous soils (Nashat, 1990; FAO, 1990; Karkush et al., 2008a; Karkush et al., 2008b, Karkush, 2008). Several examples illustrate the structural damage caused by building on gypseous soils. For instance, the foundation of the Samarra tourist hotel experienced issues due to dissolved gypsum from soil affected by a leaking fire hydrant. Similarly, the Dujail communication center suffered structural tilting.

Moreover, Al-Neami (2000) gave examples of the damages of structures founded on gypseous soils, such as: Military Housing in Salah El-Dean governorate, where cracks were observed in the walls of structures and folds in their floors as a result of the soil collapse. In the Air Force College (1975), cracks were observed in the runways. Subsequently, an improvement program was implemented on the gypseous soil of runways by injecting chemical additives, but the same problem raised in 1985 due to soil settlement.

Soil durability is the ability of soil to withstand physical and chemical impacts from the environment, as well as from any mechanical loading. Several factors influence soil durability, including soil composition, moisture content, compaction, and density (Holtz et al., 1981; Fredlund, 1993; Mitchell & Soga, 2005). Nano-technology is one of the most effective technologies used to enhance gypseous soils. The use of nano-particles as stabilizers has gained significant attention due to their small size. Typically ranging in diameter from 1 nm to 111 nm, nano-particles possess a large specific surface area. It is widely recognized that incorporating nano-particles into soils can modify their mechanical, chemical, and physical properties (Roco, 1990; Karkush et al., 2020). Many previous studies have examined the effects of various ratios of nano-materials on the behavior, durability, and shear strength of gypseous soils. For example, Karim et al. (2015) conducted a detailed analysis of the micro-structure of gypseous soils collected from three locations in northern Baghdad, Iraq: Baiji, Tikrit, and Samarra. SEM images revealed significant microstructural changes, including the presence of voids and gypsum fibers acting as binding agents. Brief immersion tests showed substantial cavities that contributed to increased compressibility in these soils due to the high solubility of gypsum. Oedometer tests were performed to assess swell stresses and compressibility of soils with different gypsum concentrations after various curing times. The results indicated that, after curing, soil compressibility gradually decreased. Under loading conditions, the connecting voids in the soil varied, leading to an increase in its permeability. The analyzed micro-structure showed that higher gypsum content resulted in reduced swell stresses and compression over longer curing periods, while lower gypsum content led to higher swell strains and greater soil compression (Al-Mukhtar & Al-Obaidi, 2022).

Karkush et al. (2020), Al-Murshedi et al. (2020), and Al-Murshedi and Karkush (2023) studied two types of gypseous soil, one from Al-Najaf city with a gypsum concentration of 42% and the other from Al-Samawa city with a gypsum content of 54%. They tested three different amounts of nano-clay and nano-silica (1%, 2%, and 4%) on the soil samples. The treated soils underwent tests to classify their physical and chemical properties, as well as to evaluate their collapsibility and shear strength in both saturated and dry conditions. The results showed that introducing nano-clay into gypseous soils had a significant effect on hydraulic conductivity and consolidation behavior. Soil samples treated with 4% nano-clay exhibited a 77% reduction in collapse potential. In a separate study, Iranpour (2016) conducted various engineering tests on soil samples from trial pits in Iran's sub-tropical regions. To evaluate the effects of selected nano-materials, a suitable collapsible soil sample was used. Several nano-materials, including nano-alumina, nano-clay, nano-copper, and nano-silica, were applied in different quantities relative to the soil's dry weight. The density and natural water content of the soil were measured during testing. The results indicated that the use of different nano-materials had varying impacts on the behavior of the collapsible soil.

Mitchell and Soga (2005) examined the impact of time on soil properties, such as deformation and strength, offering strategies for defining and calculating these outcomes. They highlighted that macroscopic stresses, including tangential and normal interparticle stresses, can be influenced by material parameters and micro-fabric variations, leading to the development of non-homogeneous strong particles within the soil.

Dunn and Mitchell (1984) explored the effect of aging time on the permeability (hydraulic conductivity) of fine-grained soils. They found that hydraulic conductivity increased as the aging time progressed, which they attributed to thixotropic changes in the sample structure. These structural alterations led to an increase in the effective pore size. They also observed an "increased degree of flocculation," noting a strong correlation between the rise in hydraulic conductivity over time and the simultaneous increase in the soil's strength and modulus. Al-Obaydi et al. (2010) utilized lime waste, a by-product, to enhance the properties of gypseous soils. They compared the combined additives of lime waste and cement with those treated using either material alone. The results revealed that the combination of lime waste and cement improved the compressive and tensile strengths of gypseous soil, making it more resistant to wetting and drying cycles. Furthermore, the combined additive reduced the amount of cement needed for stabilization by 50%. Changizi et al. (2022) investigated the use of nano-particles to enhance the mechanical properties of clay subjected to freeze-thaw cycles. The results showed that nano-SiO_2 improved clay resistance and prevented its reduction. According to the Unified Soil Classification System (UCS), the shear strength of treated clay was found to be 16% and 21% higher, respectively, compared to that of natural clay.

The current study examines the durability of gypseous soil with 80.4% gypsum content treated with various ratios of nano-silica (1%, 2%, 3%, 4%, and 5%). Durability tests, including aging, wetting-drying, and freezing-thawing cycles, were conducted. The durability was assessed based on the unconfined compressive strength of the soil both before and after treatment.

EXPERIMENTAL WORK

Gypseous Soil and Study Area

The gypseous soil contains a significant amount of gypsum salts (gypsum is a sulfuric acid salt) and can be categorized into two classifications: those with a gypsum salt content exceeding 50%, and those with a gypsum salt content below 50%. According to ASTM D5333 (1996), there are five types of soil based on gypsum percentage. The soil used in this study was collected from a location near Badra city, at the Iraq-Iran border area in Wasit province, Iraq. Block specimens were extracted from a depth ranging from 0.6 m to 1.2 m. *In-situ* work included measuring the water content and total unit weight of the soil samples. The samples were then transported to the laboratory and stored in polyethylene bags to protect them from temperature and humidity effects. The soil parameters are summarized in Table 1 (Ali & Karkush, 2024), and the Field Emission Scanning Electron Microscope (FESEM) image of the soil sample is shown in Figure (1).

Table 1. The physical characteristics of the gypseous soil (Ali & Karkush, 2024)

Property	Magnitude
In-situ unit weight, kN/m^3	14
In-situ moisture content, %	11
TSS, ppm	68
SO_3, %	39.34
pH	7.21
Cl, %	0.4936
Gypsum content, %	80.4
EC, μS/cm	1638

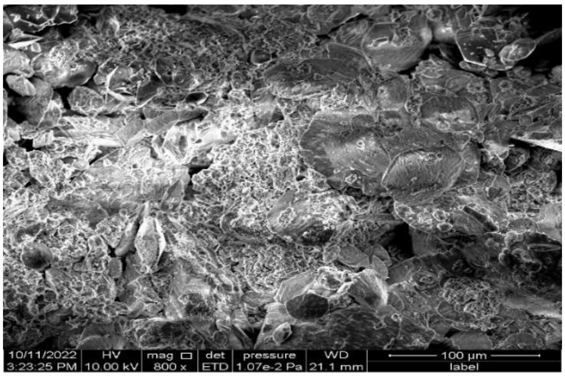

Figure (1): Field emission scanning electron microscope image for gypseous soil

Nano-silica

Nano-silica is recognized as one of the most widely used nano-materials in geo-technical engineering research. It enhances soil strength and stiffness due to its strong pozzolanic activity, small particle size, ability to fill voids, and large surface area per unit mass (Al-Murshedi et al., 2020). The characteristics and atomic composition of the nano-silica used in this study are provided in Table 2.

Table 2. The characteristics and atomic composition of nano-silica

Property	Value	Chemical composition	Content, %
Color	White	SiO_2	99.8
Electrical conductivity, μS/cm	25	Na	0.015
Fineness	15 nm	Fe	0.003
Bulk unit weight, kN/m^3	0.44	Ca	0.005
Moisture, %	1.6	Mg	0.004
Special surface area, m^2/g	200	Pb	0.0001
pH value	4.8	As	0.00001

Durability Tests

The preparation process of soil samples treated with nano-silica involves adding nano-silica to the soil. Initially, the soil samples are dried at a temperature of 45°C to prevent changes in the gypsum content. The dried soil is then divided into five equal parts, with the appropriate amounts of nano-silica (1%, 2%, 3%, 4%, and 5%) added to each part separately. The natural-soil sample is designated as N0, and the soil samples mixed with nano-silica are designated as N1, N2, N3, N4, and N5, respectively. The soil and nano-silica are thoroughly mixed to ensure homogeneity. Next, distilled water is added to the mixture and well mixed to match the *in situ* moisture content (Fredlund, 1993). The durability tests performed in this study include aging, wetting-drying cycles, and freezing-thawing cycles, with durability being assessed based on unconfined compressive strength tests.

Aging Effect

The aging phenomenon refers to a material state that reflects changes over time, leading to significant alterations in the mechanical and physical properties of soil. For gypseous-soil samples treated with nano-silica, these changes over time should be considered in geo-technical design. In general, aging tends to improve the geo-technical properties of soil, but it can sometimes have negative effects on the physical characteristics and chemical composition of the soil (Schmertmann, 1991). This research investigates the aging effect on the unconfined compressive strength of soil before and after treatment with nano-silica. Tests were conducted after treatment durations of 0, 7, 14, 21, and 28 days. The testing procedure can be summarized by the following points:

a) Molding specimens of gypseous soil before and after treatment by nano-silica, using molds having dimensions: diameter, D=38 mm and height, H= 76 mm.
b) Determining the average diameter and height of soil samples.
c) Determining the water content of soil samples.
d) Covering the specimens with polyethylene sheets and keeping them in a container.
e) Testing the unconfined shear strength for soil specimens after 0, 7, 14, 21, and 28 days of treatment for each ratio of nano-silica added to the gypseous soil.

Wetting-drying Cycles Test

The wetting-drying cycles test is crucial for assessing the geo-technical properties of gypseous soils subjected to moisture-content variations. The wetting and drying process causes the dissolution and subsequent recrystallization of gypsum, leading to expansion and contraction of the soil structure. This can result in significant volume changes which negatively impact the stability of construction (Estabragh et al., 2014). Wetting increases gypsum dissolution, which affects the shear-strength parameters of the soil. Later, the cementing of gypsum can weaken the bond strength, continuously reducing the soil's overall strength (Estabragh et al., 2014). Several factors influence how gypseous soils respond to wetting-drying cycles, including gypsum content, compaction, density, number of wetting-drying cycles, temperature, and humidity (Al-Mukhtar et al., 2012; Estabragh et al., 2015; Tang et al., 2016; Nabil et al., 2020). The ASTM D4843 specification (2016) is used to evaluate the impacts of wetting-drying cycles on the unconfined compressive strength of gypseous soil treated with nano-silica. The test procedure includes the following steps:

a) Molding specimens of gypseous soil, both before and after treatment with nano-silica, with molds having dimensions: diameter (D = 38 mm) and height (H = 76 mm).

b) Determining the average diameter and height of soil samples.
c) Determining the water content of soil samples.
d) Storing the soil samples at room temperature (25±2°C) for 24 hours.
e) At the end of the storge, submerging the specimens in potable water at room temperature for 48 hours.
f) Determining the weight of soil samples.
g) Placing the specimens in the oven at 60°C for 48 hours, then removing them from the oven. Determining the diameter, height, and weight of soil samples.
h) Continuing the procedure for 0, 1, 3,6, 12 and 24 cycles.
i) At the end of each cycle, determining the unconfined compressive shear strength.

Freezing-thawing Cycles Test

Freezing-thawing cycles refer to the repeated process of water freezing and thawing, particularly in regions experiencing extreme temperature fluctuations. This process leads to several changes in the geo-technical properties of soil, which can affect its stability and performance. These changes include:

- Soil aggregates can break down due to cycles of freezing and thawing, leading to a finer texture and increasing the potential for soil erosion. However, some studies suggest that these cycles may help in reconstructing the distributed soil particles (Oztas & Fayetorbay, 2003; Özgan et al., 2015).
- The freezing and thawing of water causes expansion, contraction, and heaving, which can lead to soil compaction and the formation of uneven surfaces (Pikul & Allmaras, 1986; Matsuoka, 2001).
- Freezing and thawing cycles in soil layers influence water movement, forming ice lenses and moisture accumulation. Thawing may result in waterlogging, altering soil porosity. Repeated freezing and thawing can reduce porosity, which in turn affects water retention and root development (Henry, 2007; Liu et al., 2017).
- Soil erosion can be accelerated by freeze-thaw activity, which forms surface crusting that is more vulnerable to wind and water erosion, leading to soil instability (Matsuoka, 2001; Zhang et al., 2021).
- Changes in bulk density reflect alterations in the mechanical and physical properties of soil, affecting the load-bearing capacity of the soil (Qi et al., 2006).

The soil samples were tested according to the specifications of ASTM D560/D560M (2016) for freeze-thaw testing. The procedure can be summarized in the following steps:

a) **Molding Specimens**: Preparing the soil samples by molding them into cylindrical specimens with a diameter of 38 mm and height of 76 mm. This is carried out for both untreated and nano-silica treated gypseous soils.
b) **Determining the Average Diameter and Height**: Measuring and calculating the average diameter and height of the soil specimens to ensure consistency in size. These measurements are important for accurate testing and analysis.
c) **Determining the Water Content**: Measuring the water content of the soil samples. This can be carried out by using an oven-drying method or a moisture analyzer, depending on the available equipment.
d) **Storing at Room Temperature**: Storing the soil samples at room temperature (25 ± 2°C) for 24 hours to allow the samples to stabilize and to avoid changes in moisture content prior to testing.
e) **Freezing the Soil Samples**: Placing the soil samples in a freezing cabinet with a constant temperature below zero°C for 24 hours. After freezing, the samples are removed from the cabinet, and their mass and water content are measured and recorded.
f) **Thawing Process**: Placing absorbent pads under the soil specimens and adding potable water to the pads. This allows the specimens to absorb water *via* capillary action during the thawing period. After thawing, the mass and dimensions of the specimens are measured and recorded.
g) **One Freeze-thaw Cycle**: Steps (e) and (f) represent one complete freeze-thaw cycle, which lasts 48 hours (24 hours of freezing + 24 hours of thawing).
h) **Repeating for Multiple Cycles**: The same procedure is repeated for 0, 1, 3, 6, 12, and 24 freeze-thaw cycles. This will allow to assess how the soil's properties change with increasing cycles of freezing and thawing.
i) **Determining Unconfined Compressive-shear Strength**: After each cycle, an unconfined compressive shear strength test is performed on the soil specimens to assess the effect of the freeze-thaw cycles on the soil's strength. The results for each

cycle are recorded to evaluate changes in the soil's mechanical properties over time.

This process will help determine how nano-silica treatment affects the durability and strength of gypseous soil under freeze-thaw conditions. The durability tests conducted on soil samples are shown in Figure (2).

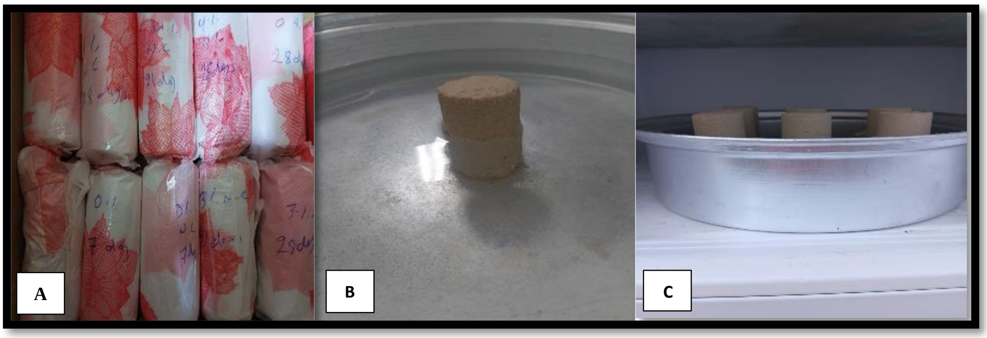

Figure (2): Durability tests: A) Storage of soil samples to measure the effect of aging, B) Wetting process for wetting-drying cycles test, and C) Freezing process for freezing-thawing cycles test

RESULTS AND DISCUSSION

Aging Effect

The unconfined compression test was performed on various soil samples to assess the impact of aging on gypseous soil before and after treatment with different ratios of nano-silica. The results are presented in Figure (3), which shows the variation of stress *versus* strain for six soil samples (N0, N1, N2, N3, N4, and N5) at different aging times (0,7, 14, 21, and 28 days). The aging time was measured immediately after the soil sample was packed. The test results demonstrated a clear trend of increasing peak stress as the aging time progressed for the soil samples treated with nano-silica. This indicates that as the soil ages, the treatment becomes more effective, leading to improved strength. Additionally, the corresponding strain at the peak stress value decreased with aging, suggesting that the soil became stiffer and more resistant to deformation over time. These findings highlight the positive effect of nano-silica treatment on the geo-technical properties of gypseous soils, particularly in terms of strength enhancement and improved resistance to strain as the aging process advances.

Figure (4) summarizes the peak stress values for each aging time, showing a clear trend that the stress increases as the storage period lengthens. This is consistent with the observations in Table 3 which also demonstrate an increase in the cohesion of the soil as aging progresses. These findings are attributed to several factors stemming from the chemical and physical interactions between nano-silica and the components of gypseous soil, as well as the natural aging processes. The key contributing reasons are:

- **Chemical Reactions**: Over time, slow chemical reactions occur between the minerals and organic components in the soil, leading to the formation of new materials. These new materials bind the soil particles together more strongly, resulting in enhanced cohesion and an increase in peak stress.
- **Compaction and Stacking**: As the soil is stored over time, natural compaction can occur. This compaction process leads to a denser soil structure, which enhances the cohesion between particles and contributes to the increase in peak stress.
- **Mechanical Improvement**: Prolonged storage allows for the reorganization of soil particles, which is facilitated by natural stresses acting on the soil. This particle reorganization improves the structural integrity of the soil and increases its resistance to deformation, thus improving the cohesion and contributing to higher peak stress values.

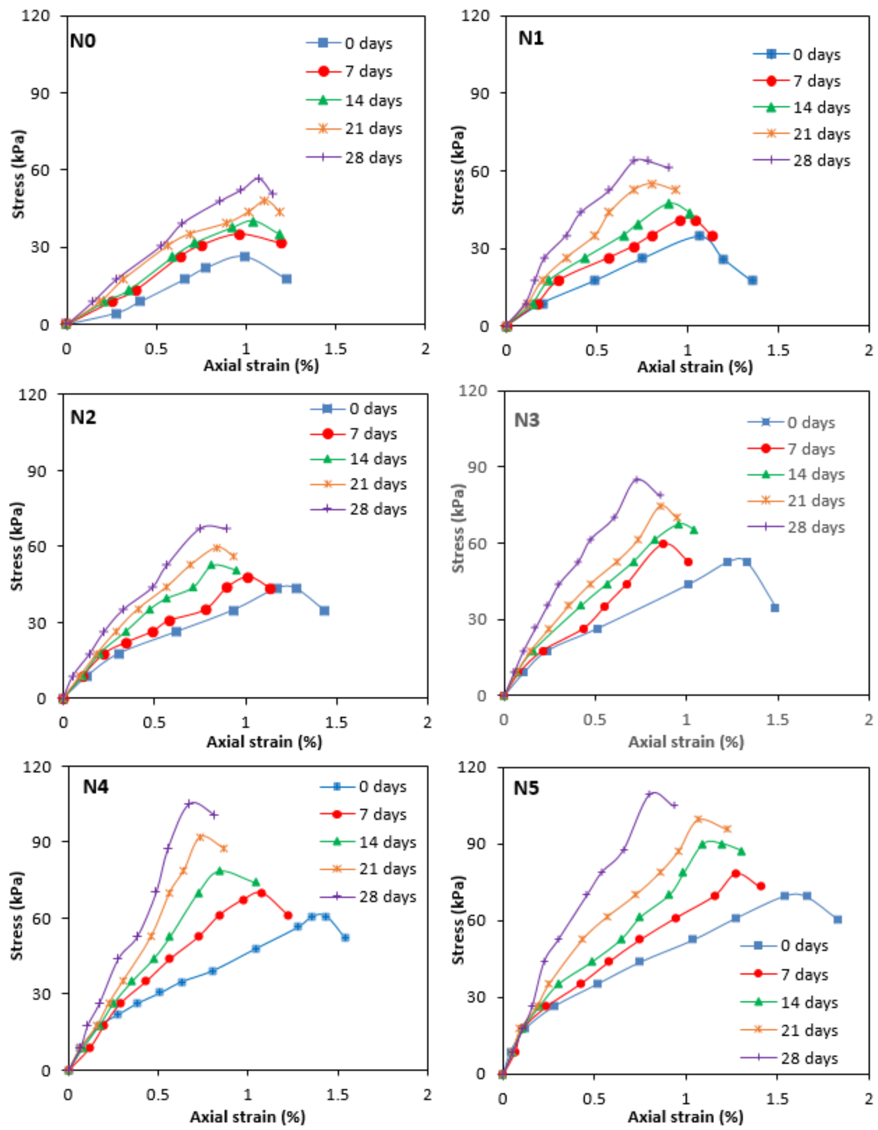

Figure (3): Stress *versus* strain curves for aging effect

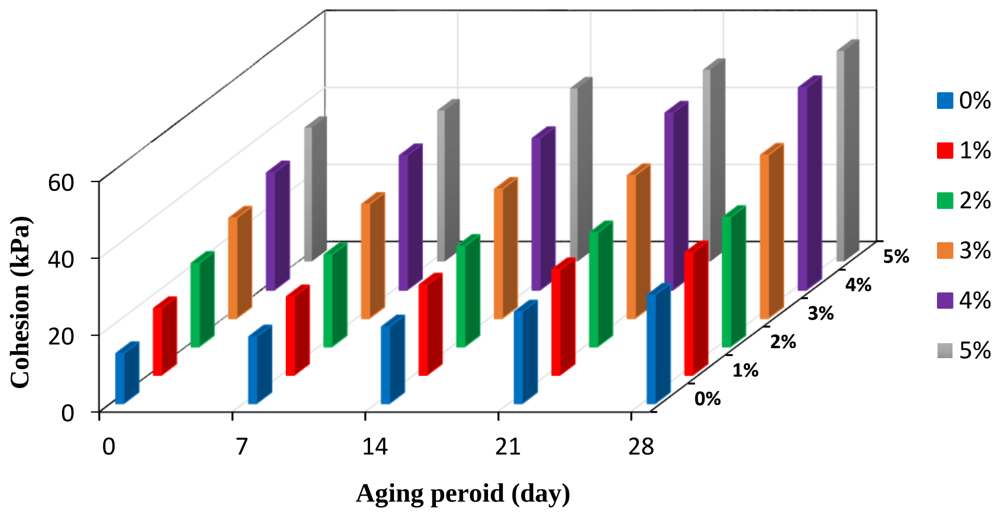

Figure (4): Variation of maximum cohesion with aging period

Table 3. Aging effect on cohesion of soil samples treated with nano-silica

Aging period (day)	Soil sample											
	N0		N1		N2		N3		N4		N5	
	Cohesion (kPa)	ω (%)	Cohesion (kPa)	ω (%)	Cohesion (kPa)	ω (%)	Cohesion (kPa)	ω (%)	Cohesion (kPa)	ω (%)	Cohesion (kPa)	ω (%)
0	13.10	11.00	17.46	11.00	21.79	11.00	26.14	11.00	30.46	11.00	34.74	11.00
7	17.47	10.20	20.53	10.32	24.01	10.43	29.73	10.52	34.91	10.83	39.19	10.88
14	20.08	9.82	23.61	10.04	26.25	10.12	33.64	10.41	39.36	10.61	44.94	10.81
21	23.99	9.10	27.57	9.5	29.74	10.02	37.17	10.31	45.97	10.46	49.75	10.54
28	28.37	8.90	31.98	9.07	33.71	9.21	42.48	10.12	52.58	10.27	54.69	10.33

The stress-strain patterns observed in this study align with those reported in previous investigations by Ltifi (1998) and Yashura and Ue (1983), reinforcing the consistency of the findings. One notable observation in the current study is the decrease in the moisture content of the soil samples as the aging time progresses. This reduction in moisture is attributed to the hydration of nano-silica and the ongoing chemical reactions between the nano-silica and the chemical compounds in gypseous soil.

As the moisture content decreases, the cohesion of the soil increases, even for the untreated soil sample (N0). The ratio of increase in cohesion with aging is reported as follows: 116, 83, 54, 62, 72, and 57% for soil samples N0, N1, N2, N3, N4, and N5, respectively. These values demonstrate that the cohesion improves over time as the soil ages and the nano-silica treatment continues to influence the soil structure. Furthermore, the increase in cohesion was found to be positively correlated with the percentage of nano-silica added to the gypseous soil. At the age of zero days, the cohesion increased by 33%, 66%, 99%, 132%, and 165% for soil samples N1, N2, N3, N4, and N5, respectively. However, at the age of 28 days, the increase in cohesion was lower, with values of 12%, 18%, 49%, 58%, and 92% for the same soil samples. Interestingly, the cohesion achieved at the age of zero days was found to be higher than the cohesion at the 28-day curing age. This suggests that while the treatment with nano-silica improves the cohesion of the soil, the initial response to nano-silica is stronger compared to the longer curing period, which could be influenced by factors, such as the hydration and bonding mechanisms within the soil.

Wetting-drying Cycles

The wetting-drying cycles lead to damage in the structure of gypseous-soil samples treated with nano-silica (N3, N4, and N5). This damage occurred due to dissolving of calcium sulphate dihydrate ($CaSO_4 \cdot 2H_2O$) in water. The exposure of gypseous soil to water leads to the dissolution of gypsum (calcium sulfate dihydrate, $CaSO_4 \cdot 2H_2O$) present in the soil. This dissolution process weakens the soil structure and reduces its cohesion, which is reflected in the loss of strength in soil samples treated with lower amounts of nano-silica (1% and 2%). This damage occurs, because the low concentration of nano-silica is insufficient to form a strong bond between soil particles, thus failing to effectively counteract the dissolution of gypsum during wetting-drying cycles.

However, when higher percentages of nano-silica (4% and 5%) are added to the gypseous soil, the bonding between the soil particles improves significantly. Nano-silica, due to its small particle size and high surface area, interacts with the gypsum and other components in the soil, facilitating the formation of new compounds, like calcium silicate hydrate (C-S-H). These new compounds contribute to a stronger and more stable structure, which helps mitigate the damage caused by gypsum dissolution. The higher the percentage of nano-silica, the stronger the interparticle bonds become, allowing the soil to maintain its cohesion and stability even after exposure to water and wetting-drying cycles. These mechanisms can be summarized as follows:

Chemical Interaction

When nano-silica is added to gypseous soil, it undergoes a chemical reaction with water to form a gel-like substance known as silica gel. This gel fills the spaces between soil particles, effectively reducing the contact between gypsum and water. As a result, the dissolution rate of gypsum is slowed down, which helps in maintaining the integrity and cohesion of the soil structure. Studies have shown that the chemical reaction between the nano-silica and the components of the soil, such as gypsum, can significantly improve the soil's geo-technical properties. This reaction helps form a more durable structure that is resistant to environmental changes, like wetting-drying cycles or freezing-thawing conditions. As Gadouri et al. (2019) and Gadouri (2023) noted, the specific soil properties and the choice of additives (like nano-silica) must be carefully considered to maximize the benefits of stabilization.

Forming Protective Layers around Gypsum Particles

Nano-silica's high surface area and strong absorption properties play a key role in improving the durability and performance of gypseous soils, especially when subjected to environmental changes, like wetting and drying cycles. When nano-silica is introduced to gypseous soil, the nano-particles are distributed across the surface of gypsum grains, forming a protective layer. This layer acts as a shield, reducing the interaction between water and the gypsum content of the soil. By doing so, nano-silica helps slow down the dissolution of gypsum, which is otherwise vulnerable to water exposure, and mitigates the negative effects associated with wetting-drying cycles. These cycles are known to significantly affect the mechanical and structural properties of gypseous soils. In particular, the dissolution and recrystallization of gypsum due to repeated wetting and drying can weaken the soil structure, leading to a loss of cohesion, reduced strength, and increased vulnerability to erosion. However, when nano-silica is used as a stabilizing agent, it helps maintain the cohesion and strength of the soil even after several cycles, as evidenced by the unconfined compressive strength (UCS) tests conducted on the soil samples after these cycles.

Figures (6) and (7) display the results of the unconfined compressive-strength tests on the soil samples after the completion of wetting-drying cycles. The UCS tests are used to assess the soil's shear strength, which is an important indicator of its stability and load-bearing capacity. The results, summarized in Table 4, provide a comparison of cohesion and moisture content in the soil samples before and after treatment with various nano-silica ratios (1%, 2%, 3%, 4%, and 5%). The data in Table 4 reflects how the wetting-drying cycles impact the shear strength of gypseous soil, highlighting the improvements brought about by the nano-silica treatment. The findings clearly show that nano-silica can significantly enhance the mechanical properties of gypseous soils, especially under conditions of environmental stress, such as wetting-drying cycles. By reducing the dissolution of gypsum and improving the bonding between soil particles, nano-silica helps maintain the integrity of the soil structure, ensuring better performance in geo-technical applications.

The incorporation of nano-silica into gypseous soil significantly enhances the soil's ability to resist the damaging effects of freezing-thawing cycles. Overall, nano-silica treatment improves the freeze-thaw resistance of gypseous soils, making them more durable and more stable under fluctuating temperature conditions. This enhancement is crucial for ensuring the performance and longevity of soil in geo-technical applications, particularly in areas subject to extreme weather conditions.

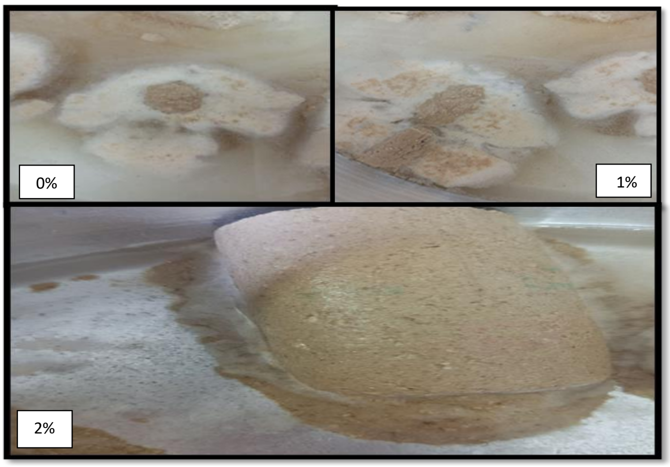

Figure (5): Damaged soil samples during wetting

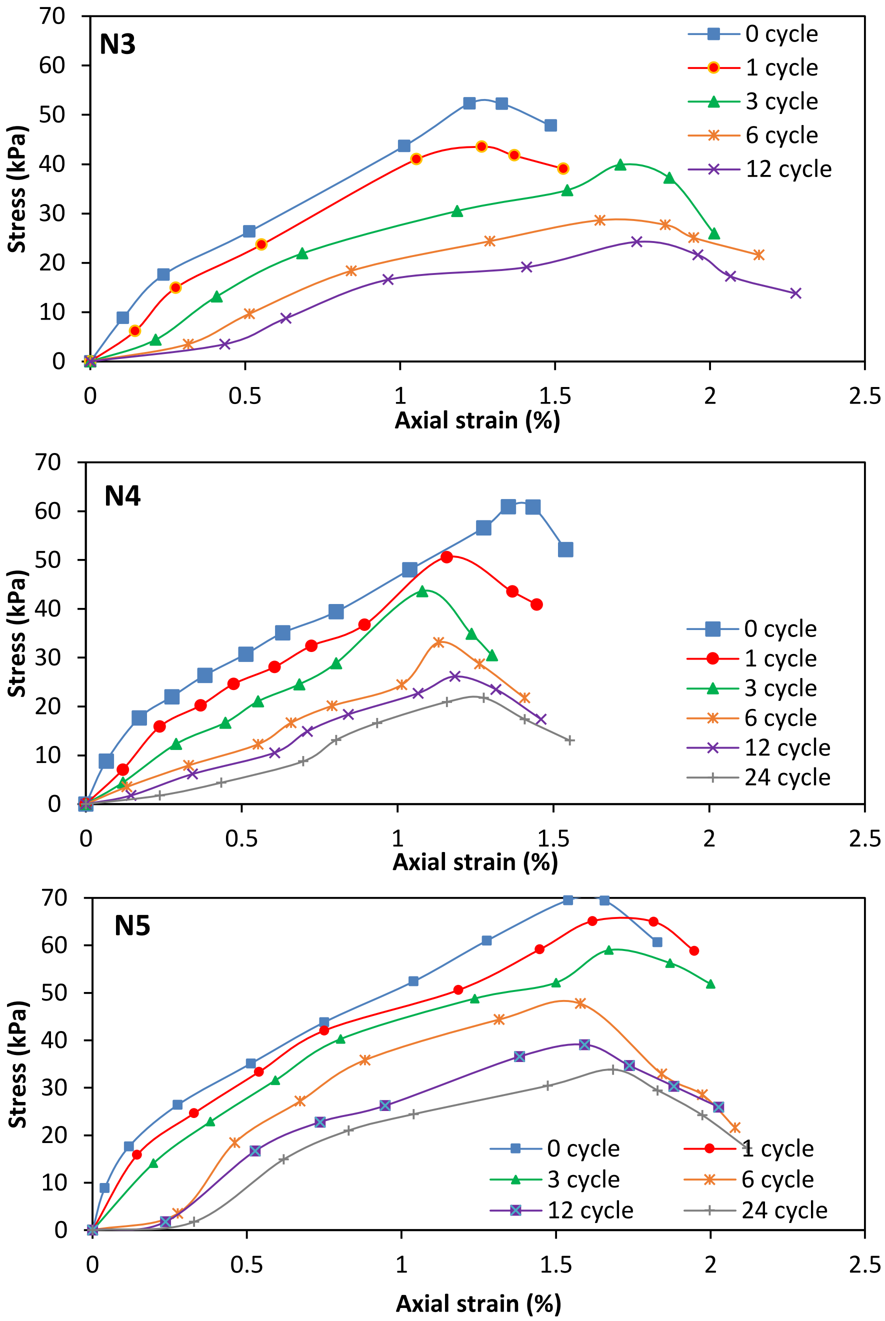

Figure (6): Stress *versus* strain curves for the wetting-drying test

Table 4. Effects of wetting-drying cycles on unconfined compressive strength of gypseous soil

Number of cycles	Soil sample								
	N0	N1	N2	N3		N4		N5	
	Cohesion (kPa)	Cohesion (kPa)	Cohesion (kPa)	Cohesion (kPa)	*ω* (%)	Cohesion (kPa)	*ω* (%)	Cohesion (kPa)	*ω* (%)
0	13.10	17.46	21.79	26.14	11.0	30.46	11.0	34.74	11.0
1	0	0	0	21.78	14.9	25.29	15.2	32.55	16.3
3	0	0	0	19.94	19.8	21.84	22.3	29.49	23.3
6	0	0	0	14.32	22.5	16.57	25.5	23.88	26.6
12	0	0	0	12.13	26.3	13.08	27.5	19.53	28.3
24	0	0	0	0	-	10.89	29.5	16.91	30.2

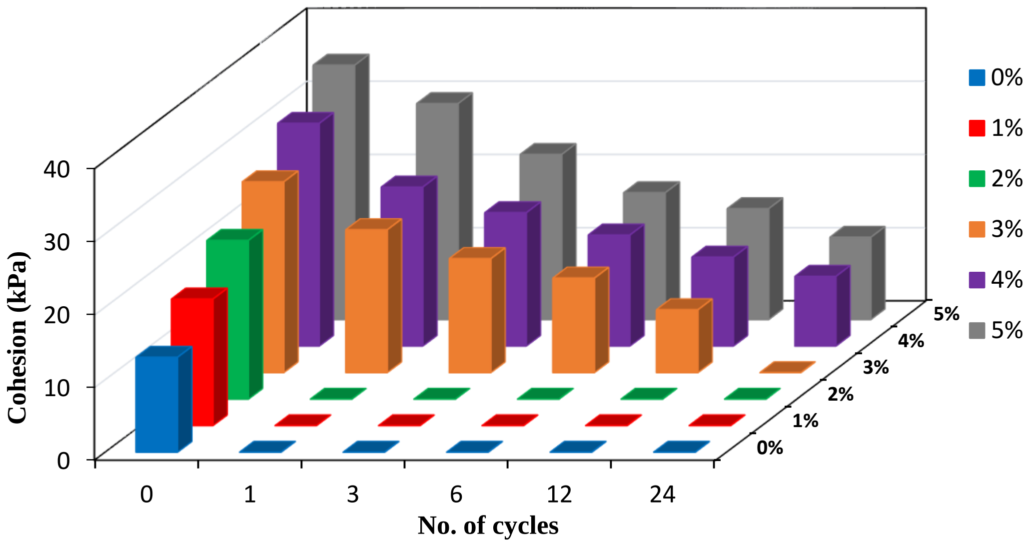

Figure (7): Variation of maximum cohesion with wetting-drying cycles

Freezing-Thawing Cycles

The unconfined compressive strength of gypseous soil samples treated with 3%, 4%, and 5% nano-silica was tested under several freezing-thawing cycles (ranging from 1 to 24 cycles). The results, including stress-strain curves for soil samples N3, N4, and N5, are shown in Figure (8). A summary of the results, focusing on the cohesion between soil particles, is provided in Figure (9) and Table 5. The effects of freezing-thawing cycles on the behavior of gypseous soil can be summarized by the following points:

- **Freezing Expansion**: When water within soil pores freezes, it expands, increasing the soil's volume and generating internal pressure. This expansion can create cracks and fissures in the soil.
- **Thaw Shrinkage**: As frozen water thaws, the soil volume returns to its original state, causing shrinkage. This shrinkage weakens the bonds between soil particles, reducing cohesion and strength.
- **Structural Weakness**: Repeated cycles of freezing and thawing weaken the internal structure of gypsum-rich soils over time. This weakening can lead to a loss of stability and cohesion.
- **Chemical Corrosion**: The exposure of gypsum soil to freeze-thaw cycles can result in chemical reactions with water, dissolving minerals and organic materials. This process leads to the loss of essential structural components in the soil, increasing erosion and weakening the soil.
- **Cracks and Fissures**: Continuous expansion and contraction lead to the formation of cracks. Over time, these cracks may grow, causing the soil's structure to deteriorate and resulting in a loss of cohesion.

Table 5. Effects of freezing-thawing cycles on unconfined compressive strength of gypseous soil

Number of cycles	Soil sample								
	N0	N1	N2	N3		N4		N5	
	Cohesion (kPa)	Cohesion (kPa)	Cohesion (kPa)	Cohesion (kPa)	ω (%)	Cohesion (kPa)	ω (%)	Cohesion (kPa)	ω (%)
0	13.10	17.46	21.79	26.14	11.0	30.46	11.0	34.7444	11.0
1	0	0	0	19.51	13.2	21.76	14.7	29.5051	16.3
3	0	0	0	15.65	15.8	18.26	16.3	22.5567	17.8
6	0	0	0	12.99	17.7	15.21	19.5	17.3328	20.5
12	0	0	0	8.67	19.5	12.19	21.5	15.1519	22.5
24	0	0	0	0	-	9.56	22.7	11.2452	23.3

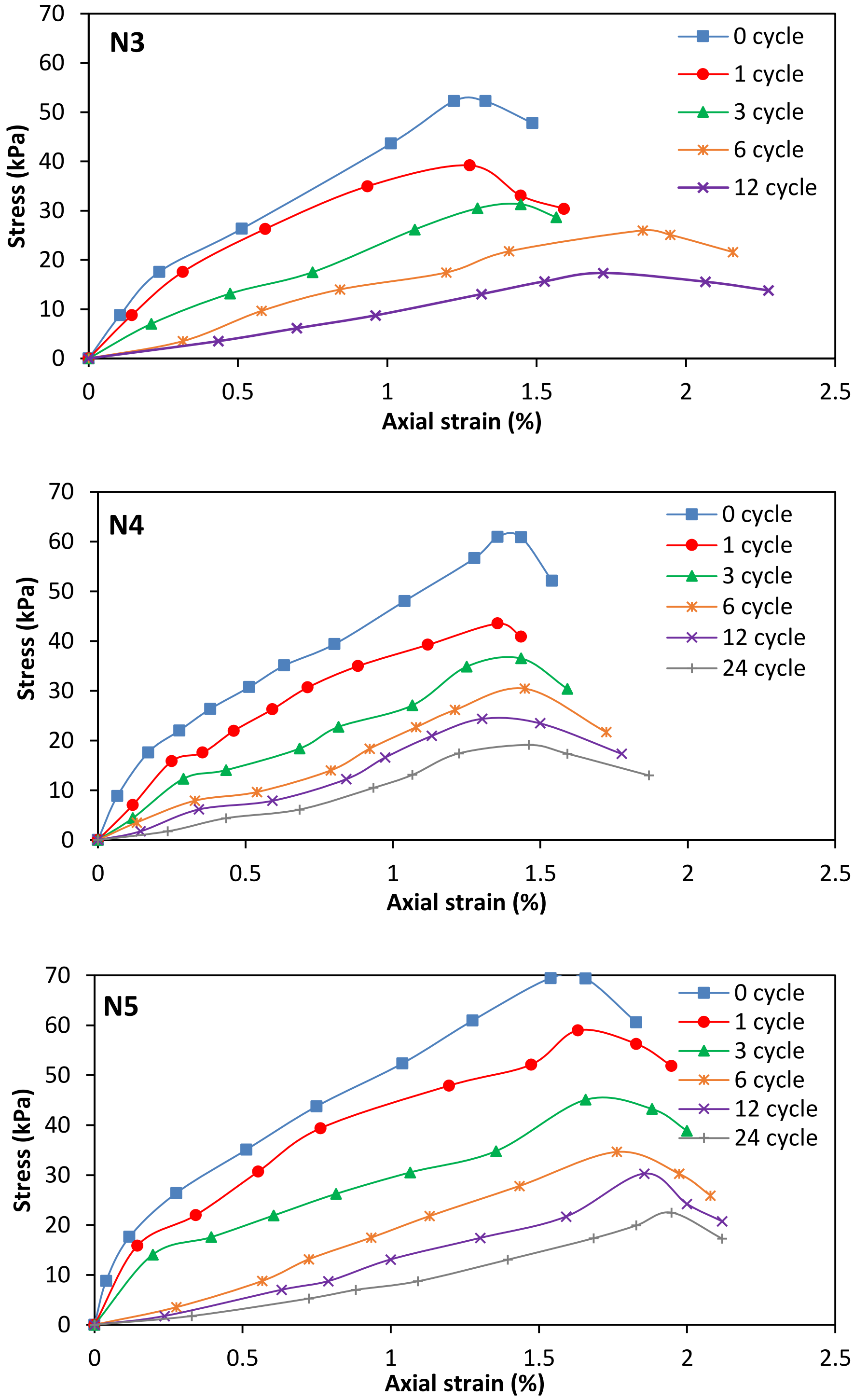

Figure (8): Stress-strain curves for soil samples N3, N4, and N5 with freezing-thawing cycles

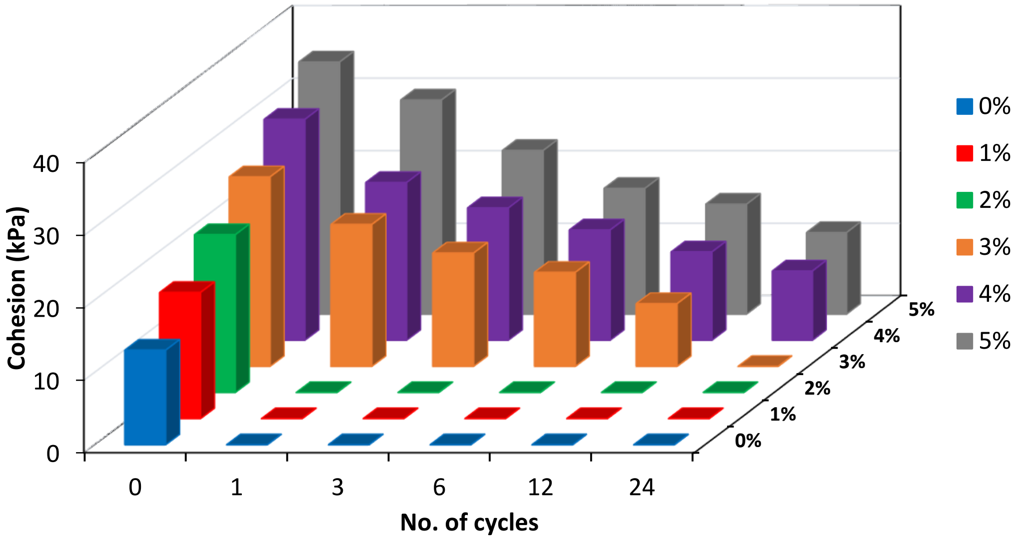

Figure (9): Variation of maximum cohesion with freezing-thawing cycles

CONCLUSIONS

After analyzing the results of the tests conducted on gypseous soil treated with nano-silica, the following conclusions can be drawn:

- The soil samples used in the tests were collected from Badra city, located at the Iraq-Iran border. These samples are classified as highly gypseous due to their high gypsum salt content.
- Nano-silica can be utilized to enhance the geo-technical properties of highly gypseous soils, due to its high specific surface area, market availability, and reasonable price.
- The aging of soil samples, both before and after treatment with nano-silica, significantly increases the unconfined compressive strength of the soil. Most of the strength gained from the treatment occurs immediately after mixing the soil with nano-silica, while further aging results in a gradual increase in strength.
- The addition of nano-silica strengthens the soil structure, improving its overall strength.
- Under wetting-drying and freezing-thawing cycles, natural gypseous soil and soil treated with 1% or 2% nano-silica were completely destroyed due to the dissolution of gypsum salts, which weakened the bonding between soil particles. Therefore, such low nano-silica concentrations are not effective.
- The optimal nano-silica percentages for enhancing cohesion and bonding between soil particles and withstanding wetting-drying and freezing-thawing cycles are 4% and 5%.
- Some limitations of using nano-materials include the need for careful handling and proper storage to preserve their chemical and physical properties. Additionally, they are considered expensive materials.

RECOMMENDATIONS

Based on the findings and conclusions, the following recommendations for future research can be made:

- Future research could focus on investigating the influence of various other nano-materials, such as nano-titanium dioxide, nano-alumina, or nano-clays, on the durability and mechanical properties of gypseous soils.
- It would be valuable to explore the performance of nano-silica in combination with other additives, such as cement, lime, or organic polymers. This approach could lead to a deeper understanding of how synergistic effects can enhance the engineering properties of gypseous soils and improve their resistance to environmental factors, like wetting-drying and freezing-thawing cycles.
- While laboratory studies provide valuable insights into the behavior of nano-silica-treated soils, evaluating the long-term stability and performance of treated soils under real-world field conditions is crucial. Future research could assess the practical

feasibility of using nano-silica for soil stabilization in construction projects, focusing on long-term durability, cost-effectiveness, and environmental impact.

- Investigating the environmental impacts of using nano-silica in soil stabilization could provide important information about its long-term effects on soil health, groundwater quality, and ecosystem sustainability. Future research could include studies on the leaching potential of nano-silica and the bio-accumulation of nano-particles in the environment.

Data Availability

Data used in this study is presented in figures and tables as a part of a Ph.D. thesis.

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