University of Baghdad
College of Engineering
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.jcoeng.edu.iq

Volume 31 Number 7 July 2025

Studying Leaching of Gypseous Soil Improved with Nanomaterials

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ABSTRACT

This study provides a comprehensive overview of the characteristics of nano-silica and nano-clay and their impact on preventing dissolved salt of gypseous soil containing high gypsum of 80.4% during the leaching process. The investigation evaluates the impact of several proportions (1, 3, and 5%) on the behavior of gypseous soil. The leaching test was performed using a physical model with a steel box (70×70×70) cm. During this leaching stress, settlement due to the leaching process, and total dissolved salts were measured. Also, after the end of the test, the remaining concentration of gypsum salt in the soil was measured. Nanomaterials exert a beneficial influence in reducing soil leaching settlement, especially for silica percentages of 4 and 5 %. All the percentages used decreased both soil settlements at range (10.49- 47.9) % and (15.26-63.23) % for soil samples improved with nano-silica and nano-clay, respectively. It also demonstrates that the utilization of nanomaterials leads to a decrease in the total dissolved salts in drainage water at a percentage of (11.65-42.89) % when using nano-silica and (10.72-57.59) % when using nano-clay. The soil's ability to resist loading and to retain the gypsum salts increased as the percentage of nanomaterials increased.

Keywords: Leaching, Nanomaterials, Collapsibility, Problematic soils, Gypseous soils.

1. INTRODUCTION

Soils that have unstable structures such as soft soil, expansive soil, and gypseous soil have been exploited to construct structures with care and improve the soil properties by different methods before construction **(Clemence et al., 1981; Jha et al., 2017; Karkush and Kareem, 2017; Ibrahim and Karkush, 2023)**. Still, the gypseous soil is not accepted as a construction medium since it has unreliable and unpredictable behavior, where it has a good bearing capacity and low degree of compressibility in a dry state, but when it is subjected to water, unexpected and sudden collapse occur and the bearing capacity decreasing about 50% **(Saaed and Khorshid, 1989; Mukhlef et al., 2020; Jawad et al., 2024)**. If this type of soil is subjected to water flow, new pores are created inside the soil mass because of the dissolution of salts. This procedure resulted in a metal-stabilized soil structure that allows

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2025.07.06

Article received: 07/11/2024
Article revised: 18/12/2024
Article accepted: 25/12/2024
Article published: 01/07/2025

for the sliding of soil particles and increasing soil density. The dissolution rate depends on several factors such as changes in moisture content, water flow, the permeability of the soil, and the type and content of gypsum salts in the soil **(Zeng and Meng, 2006; Almurshedi and Karkush, 2023)**. Several methods and techniques were used previously to improve the geotechnical behavior of gypseous soil, especially to reduce the effect of leaching and loss of strength upon wetting, but still, there is no active technique that can be used to solve such problems **(Salman et al., 2022)**.

Nanotechnology is commonly used in geotechnical engineering in several ways: 1) Investigating soil structure at the nanometer scale to enhance our comprehension of soil composition, 2) studying the effect of adding various nanostructured materials on the geotechnical properties, and 3) At the atomic or molecular level, nanomaterials are used to enhance soil by acting as an external support to the soil structure **(Nel et al., 2006; Emad and Salman, 2024).** Several researchers showed the impact of nanomaterials to improve gypseous soil such as: **(Al-khafaji and Al-Janabi, 2024)** studied the influence of lime and nano CaCO3 mixture to decrease the collapsibility of two types of Karbala gypseous soils with gypsum content of 51 and 2%. The mixture was added in different percentages. The optimal ratio of treatment was (1% nano-$CaCO_3$ + 3% lime) or (0.5% nano-$CaCO_3$ + 7.5% lime) for first soil and for second soil, the optimal treatment ratios were (0.5% nano-$CaCO_3$+ 3.5% lime), (1% nano-$CaCO_3$+ 3% lime), (0.25% nano-$CaCO_3$+ 7.25% lime), or (1% nano-$CaCO_3$ + 7% lime).

(Ali and Karkush, 2024) investigated the impact of nan-clay on the engineering properties of gypseous soil with 80.4% gypsum content. The results demonstrate that the nano-clay increased shear strength parameters, optimum water content, and liquid limit and decreased the collapse index, specific gravity, and maximum dry density of soil. This article focuses on the properties of gypseous soil treated with nano silica and nano clay. It also shows the impact of the leaching process on gypseous soil using a physical model.

This study focuses on the leaching behavior of gypseous soil using a physical model that was locally manufactured. Also, to investigate the influence of nano-silica and nano-clay to improve gypseous soil

2. DISTRIBUTION OF GYPSEOUS SOIL AND ITS GEOTECHNICAL PROPERTIES

A substantial concentration of gypsum salts is the defining characteristic of gypseous soils, which are most commonly found in dry and semi-arid regions of the world, including certain countries in Africa, Central Asia, and southern Asia. Iraq is one of the Asian countries in which about 31.7% of the total area is covered with gypseous soil **(Agriculture Organization of the United Nations, 1990; Ismail, 1994)**. Several researchers studied the chemical and geotechnical properties of gypseous soils collected from several sites in Iraq and the world and having different gypsum content. Gypsum is available in various shapes, including 1) dihydrate which consists of calcium sulfate bound to two water molecules, 2) hemihydrate contains half a molecule of water for every molecule of calcium sulfate, and 3) anhydrite consists of calcium sulfate only with no water molecules bound **(Al-Barazanji, 1973; Al-Dabbagh et al., 1990; Solis and Zhang, 2008; Al-Saoudi et al., 2013; Kuttah and Sato, 2015; Dana, 2022)**. The effect of heating on the molecules of water in the gypsum is shown in **Fig. 1 (Herrero and Porta, 2000; Yılmaz, 2001; Solis and Zhang, 2008; Kuttah and Sato, 2015)**.

Solubility is the primary determinant influencing the behavior of gypseous soils and is accountable for the formation of sinkholes and cavities in the soil mass. The solubility of the hydrated gypsum varied between 2.2 and 2.6% gm/l in purified water **(Hesse and Hesse, 1971; Rodrigues and Vilar, 2010; Al-Saoudi et al., 2013)**.

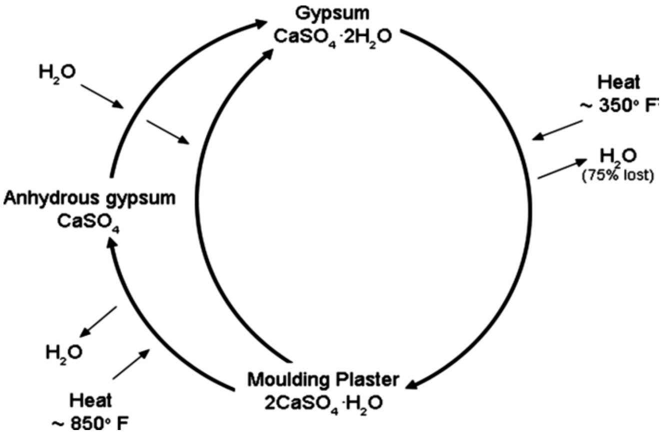

Figure 1. Gypsum cycles.

3. SOIL SAMPLING AND STUDY AREA

Gypseous soil utilized in this research was extracted from Badra city at the Iraq-Iran border area/Wasit province/Iraq. The depth at which specimens were acquired ranged from 0.6 to 1.2 m. The field water content and density of soil were measured. Then soil samples were covered with nylon bags and transported to the laboratory. The soil characteristics are summarized in **Table 1,** and the particle size distribution curve is shown in **Fig. 2**.

Table 1. Badra gypseous soil properties.

Soil classification	Low plasticity silty soil (ML)	Specifications
Gypsum content, %	80.4	Al-Mufty and Nashat equation
Specific gravity, Gs	2.45	**(ASTM D854-10, 2010)**
Maximum dry density, g/cm^3	1.60	**(ASTM D698-12, 2012)**
Optimum water content, %	14.80	
Liquid limit, %	22	**(ASTM D 422-63, 2007)**
Hydraulic conductivity, cm/s	3.61E-05	**(ASTM D5084-10, 2010)**
Collapsible index, %	9.05	**(ASTM D 5333-03, 2003)**
Cohesion, kPa	10.01	**(ASTM D2850-15, 2015)**
The angle of internal friction, Degree	19.86	

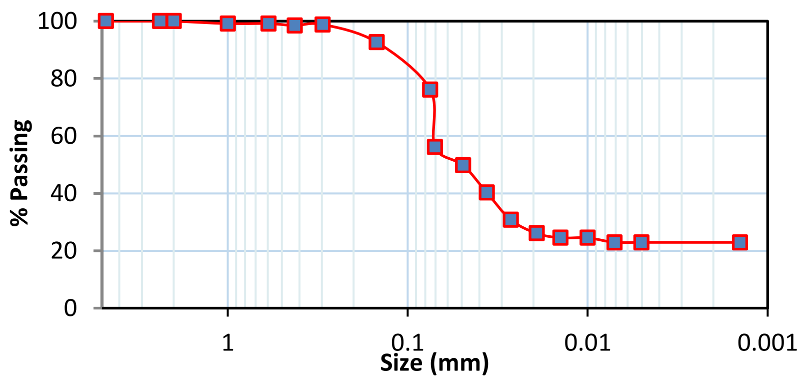

Figure 2. Particle size distribution curve.

The reason for choosing this soil because it was not studied by previous researchers. Also, noticed that there are buildings near the soil location. In addition, it is planned to build a hospital on this site.

4. NANOMATERIALS AND PREPARATION OF SOIL SAMPLES

Two types of nanomaterials are used in this study (nano-silica and nano-clay) with different percentages of 1, 3, and 5%. Nanomaterials enhance the soil's strength and stiffness through their strong pozzolanic activity because of their distinctive properties, such as small particle size, capacity to fill empty spaces, and large surface area per unit mass **(Taha and Taha, 2012; Barbhuiya et al., 2021; Karkush et al., 2023)**. Physical properties and chemical composition of nanomaterials are shown in **Table 2**.

Table 2. Physical properties and chemical composition of nanomaterials.

Nanomaterials	Nano-silica			Nano-clay		
Property	Value	Chemical composition	Content, %	Value	Chemical composition	Content, %
Mineral type	-	-	-	Montmorillonite	SiO_2	68
Color	White	SiO_2	99.8	Pale white	AL_2O_3	25
Electrical conductivity, µS/cm	25	Na	0.015	25	K_2O	1.2
Fitness, nm	15	Fe	0.003	10	Na_2O	1.6
Bulk density/cm^3	0.044	Ca	0.005	0.7	MgO	0.3
Moisture, %	1.6	Mg	0.004	0.5	TiO_2	0.2
surface area, m^2/g	200	Pb	0.0001	220-270	CaO	0.3
pH value	4.8	As	0.00001	-	-	-

Nanomaterials were kept in a good manner to avoid exposure to heat and humidity and were prevented from clumping together. The soil samples were prepared according to the field dry unit weight and field water content; a specified amount of soil sample was divided into four parts. Add nanomaterial to each part and mix for a sufficient time in a good manner to get a homogenous mixture. After that, add a specified water content and continue blending the mixture. After that, all parts were collected together to mix all materials and ensure a homogeneous distribution of nanomaterials. The definition of soil samples is represented in **Table 3**.

Table 3. Soil samples definition.

Soil samples	Definition
N	Natural gypseous soil
S1	Gypseous soil improved with 1% nano-silica
S3	Gypseous soil improved with 3% nano-silica
S5	Gypseous soil improved with 5% nano-silica
C1	Gypseous soil improved with 1% nano-clay
C3	Gypseous soil improved with 3% nano-clay
C5	Gypseous soil improved with 5% nano-clay

5. PHYSICAL MODEL AND LEACHING PROCESS

5.1 Physical Model

The device used for leaching tests is manufactured locally, as shown in **Fig. 3**. It consists of several parts, a steel container with a cross-section of 700×700 mm and a height of 700 mm. It contains an underneath beam used as support (600 mm width and 3 mm thickness). Also, contains three valves, two at the top of the container at a distance of 51 mm from the base of the container with a diameter ¾ in used one for inlet water and the other used for overflow, and the other one at the bottom end with 1 in diameter used for outflow of water.

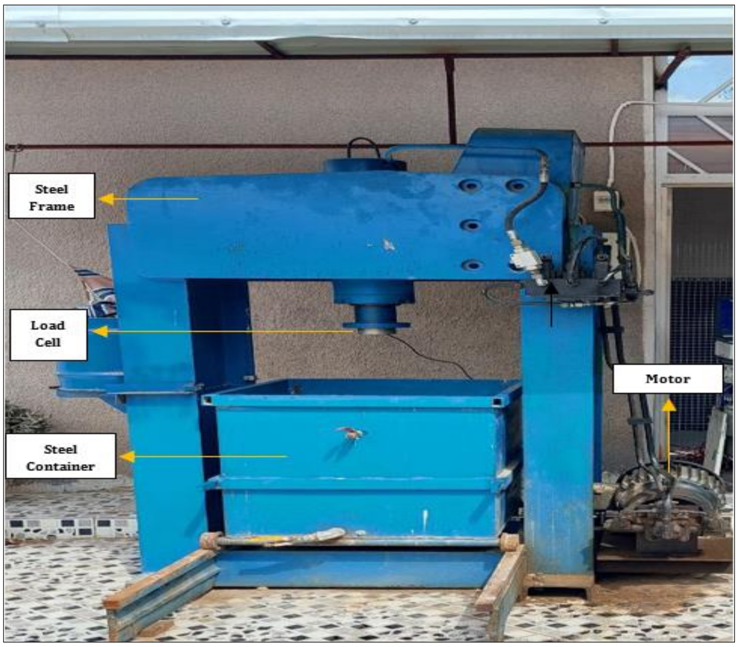

Figure 3. Physical model used in leaching tests of gypseous soil.

A steel loading frame with dimensions (length = 1210 cm, width = 220 mm, and height = 2000 mm) is used to apply the vertical load on the plate (100×100) mm, and a Compaction hammer is used to compact soil samples in a container. Electric parts include a hydraulic jack used to apply the axial load through a hydraulic cylinder based on Pascal's law. According to the hydraulic jack catalogue, the highest load to be added is about 70 tons, and a load cell transducer is used to convert a mechanical force to an electrical signal. This signal is used to calculate the applied force. The type of load cell used in this research is the DYLF-102 model, and it has a capacity equal to 7 tons.

5.2 Leaching Process

Before and after improved soil, leaching tests were carried out using the physical model. The tests were performed under different leaching stresses but under constant hydraulic gradient (6) and leaching time. The hydraulic gradient was chosen in order not to affect the orientation of soil particles during the leaching process **(Khuzaie, 1985)**. The data measured from these tests are the concentration of total dissolved salts in the water that drains from the soil box, the soil settlement due to the dissolved gypsum, and the concentration of the remaining gypsum in the soil after the end of the test at different depths soil sample. The leaching test procedure includes (1) Preparation of the soil samples in the soil container of the model. The vertical stress is applied and graduated at a constant rate. When the value of settlement reached 10 mm, the value of vertical stress was recorded. (2). The value of vertical stress settlement remains constant along the period of saturation and the leaching process. The saturation process was started by the flow of water from the top of the soil samples to the bottom (DWF), preventing water drainage from the bottom of the soil sample. The leaching process begins when the soil samples become fully saturated after 24 hr. (3) The time of leaching test for 11 days. Soil settlement was measured using the LVDT sensor, and the concentration of TDS was measured every 6 hours. Also, the percentage of gypsum content that remains in the soil after the test is measured at different depths.

6. RESULTS AND DISCUSSIONS

The results of stress that remain constant along the period of leaching measured during dry conditions correspond to 10 mm settlement as represented in **Table 4**. The value of stress increased by a good percentage as the percentage of nanomaterials increased because the nanomaterials have a higher ability to fill the voids between soil particles and decrease the soil's ability to compress under loading. Also, Nano-materials enhance soil stiffness, meaning that it requires more load to achieve the same amount of settlement compared to untreated soil. Gypsum dissolves easily in water, causing the soil to disintegrate when exposed to water flow. This can lead to a loss of cohesion and the appearance of voids in the soil as it acts as cementation and bonding materials between soil particles **(Karkush et al., 2008; Ahmed and Ugai, 2011; Kalinski, 2021)**. The nanomaterials caused to decrease in the value of settlements due to the leaching process because these types of materials have several benefits such as improved cohesion and strength, reduced permeability, increased chemical stability, and prevented internal corrosion **(Al-Obaydi, 2003; Kannan et al., 2022; Karkush et al., 2008; Almurshedi and Karkush, 2023; Chaudhary et al., 2024)**. Nano-silica and nano-clay decreased the settlement of soil in a percentage range between 10.48-47.89% and 15.26-63.23%. Also, noticed the nano-clay material had more effect in enhancing all the properties of gypseous soil and decreasing the leaching settlement. The variations of settlement with time are shown in **Figs. 4 and 5**.

Studying and investigating the concentration of dissolved salt is very important to provide brief details and data about the gypseous soil of Badra city/Wasit province of Iraq. Also, if the concentration of dissolved salts in the outflow water is a higher value causes increased settlement and leads a large damage to the construction building **(Al-Mufty, 1979; AL-Sharrad, 2003; Seleam, 2006; Abbeche et al., 2010)**. So, the concentration of total dissolved salts in the drainage water is measured for gypseous soil and gypseous-nanomaterial soil.

Table 4. Results of leaching tests.

Soil samples	Leaching stress, kPa	Leaching settlement, mm	Maximum total dissolved salts, ppm
N	255	26.41	54205
S1	273	23.64	47890.12
S3	354	18.92	36799.77
S5	603	13.79	30951.15
C1	280	22.51	48394.22
C3	379	17.02	35775.3
C5	662	9.71	22990.36

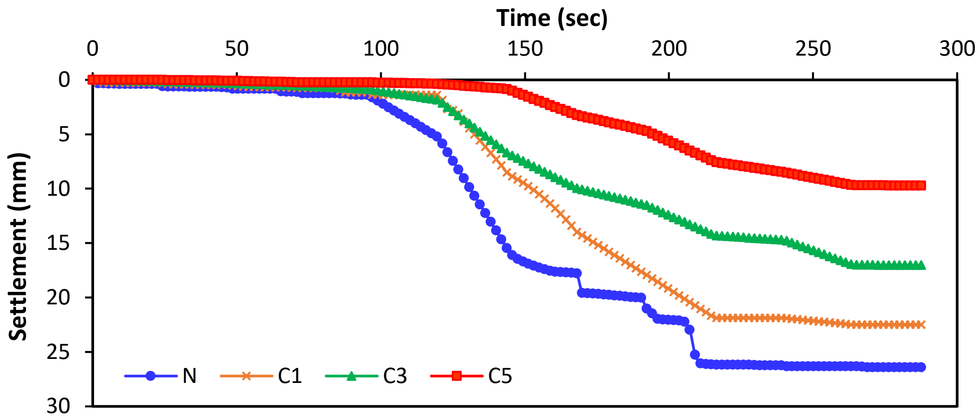

Figure 4. Variation of soil settlement with time of gypseous soil and gypseous-clay soil samples.

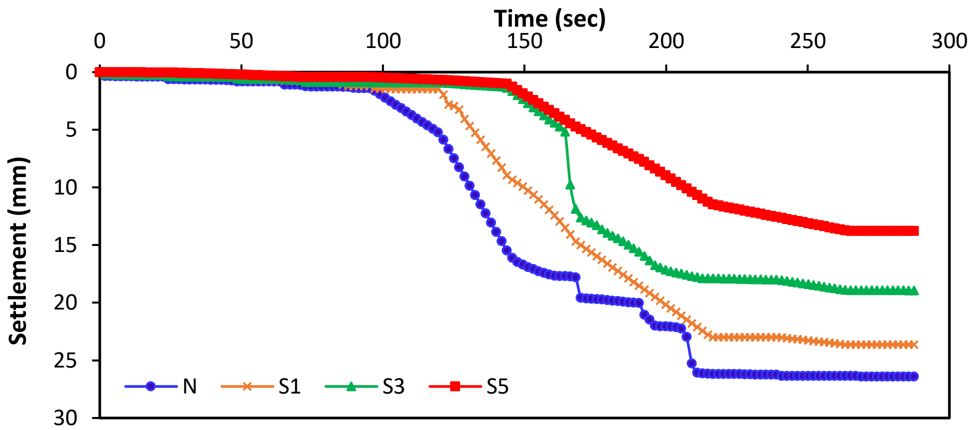

Figure 5. Variation of soil settlement with time of gypseous soil and gypseous-silica soil samples.

The results in **Figs. 6 and 7, and Table 5** show that nanomaterials lead to a decreased value of TDS because they coat gypsum particles and prevent them from dissolving. After the end of the test, the gypsum content that remained in the soil samples was measured at different depths along the soil sample.

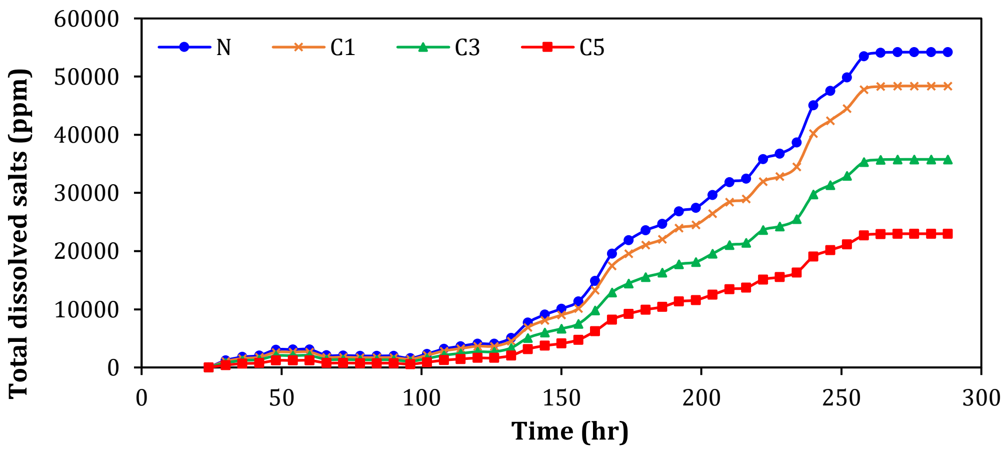

Figure 6. Variation of total dissolved salts with time of gypseous soil and gypseous-clay soil samples.

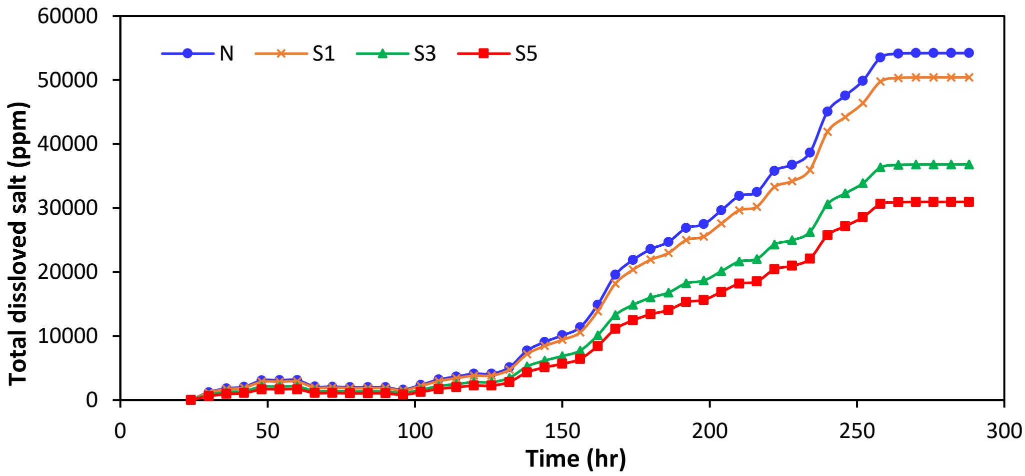

Figure 7. Variation of total dissolved salts with time of gypseous soil and gypseous-silica soil samples.

The gypsum salts in the soil at the surface of the soil are the minimum value and maximum value at the bottom because of leaching process starts from the top to bottom and causes precipitation of salts at the bottom. The percentage of gypsum in soil samples that contained nanomaterials was higher than in natural gypseous soil because it led to keeping gypsum in the soil and preventing it from dissolving.

Table 5. Results gypsum content after leaching tests.

Depth	Soil samples						
	N	S1	S3	S5	C1	C3	C5
0	14.95	19.51	35.84	42.86	21.93	37.07	52.41
20	21.95	26.51	42.84	49.86	28.93	44.07	59.41
40	28.95	33.51	49.84	58.86	35.93	51.07	68.41

7. CONCLUSIONS

In this research, the soil samples are obtained from Badra city in Wasit province in Iraq. This soil is classified as silty soil with low plasticity and contains higher gypsum content (80.4%), so it is considered severe trouble gypseous soil. The leaching process was conducted on soil samples using a physical model manufactured locally. The flow of water was downward flow with a hydraulic gradient (6). The leaching stresses used in this study correspond to 10 mm settlement under dry conditions. All the results showed that the addition of nanomaterials leads to enhanced soil properties. It led to a decrease in the value of leaching settlement and total dissolved salts. It still caused an increase in the percent of gypsum content in the soil after the end of the test because it coated the gypsum particles and protected them from the effect of water. Also, it showed the impact of nano-clay more than nano-silica on improving gypseous soil.

Acknowledgements

The authors are grateful to the staff and professors of the Department of Civil Engineering, College of Engineering, University of Baghdad, who significantly facilitated this study.

Credit Authorship Contribution Statement

Shahad D. Ali: Writing – review & editing, Writing – original draft, Methodology. Mahdi Karkush: Writing – review & editing, and Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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دراسة الغسل في التربة الجبسية المحسنة باستخدام المواد النانوية

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الخلاصة

تغطي التربة الجبسية 31.7% من إجمالي مساحة العراق وتتواجد أغلبها في المناطق شبه الجافة في العالم. ولا يفضل استخدام هذا النوع من التربة في تشييد المباني والمنشآت لأنها تتسم بتشوهات حجمية عالية عند تعرضها لعملية الترطيب. تعتبر المواد النانوية من التقنيات الفعالة المستخدمة في معالجة وتحسين الخواص الجيوتقنية للتربه الجبسية وتقدم هذه الدراسة نظرة شاملة عن خصائص النانو سيليكا والطين النانوي وأثرها في منع تكون الأملاح الذائبة في الترب الجبسية المحتوية على نسبة عالية من الجبس 80.4% خلال عملية الاستخلاص. تم دراسه تأثير نسب مختلفه من المواد النانويه (1، 3، 5%) على سلوك الترب الجبسية وقد تم اجراء اختبار الاستخلاص باستخدام نموذج فيزيائي بصندوق فولاذي (70×70×70) سم وخلال عملية الاستخلاص هذه تم قياس إجهاد الاستخلاص والترسيب الناتج عن عملية الاستخلاص والأملاح الذائبة الكلية. كما تم قياس تركيز الأملاح الجبسية المتبقية في التربة بعد انتهاء الاختبار، حيث أظهرت المواد النانوية تأثيراً إيجابياً في تقليل الهبوط للتربه الجبسيه بنسب تتراوح بين (10.49− 47.9) % و (15.26− 63.23) % لعينات التربة المحسنة بالنانو سيليكا والطين النانوي على التوالي، كما تبين أن استخدام المواد النانوية يؤدي إلى انخفاض إجمالي الأملاح المذابة في المياه وكذلك زادت قدرة التربة على مقاومة التحميل والاحتفاظ بأملاح الجبس مع زيادة نسبة المواد النانوية.

الكلمات المفتاحية: غسل التربة، المواد النانوية، الانهيارية، الترب ذات المشاكل، التربة الجبسية.