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ORIGINAL

Strengthening Gypsum Soils: The Role of Lime and CaCO3 Nanoparticles in Enhancing Suction and Compressive Strength

Fortalecimiento de suelos de yeso: El papel de la cal y las nanopartículas de CaCO3 en la mejora de la succión y la resistencia a la compresión

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ABSTRACT

This study examines the characteristics and stabilization of two types of gypsum soils, known for their high gypsum content, which affects their physical and chemical properties. Gypsum soils pose challenges in construction due to their solubility in water, leading to instability. The research focuses on the interaction of moisture content, gypsum concentration, and soil structure under different climatic conditions.
The study evaluates the relationship between soil total suction, measured by the filter paper approach, and unconfined compressive strength in both natural and processed gypsum soils. Stabilization techniques using CaCO3 and lime nanoparticles (NPs) were explored. The connection between compressive strength and total suction was established through the degree of saturation obtained from the soil water characteristic curve and optimal water content.
Results showed that for SG50 soil, the maximum compressive strength increased with treatment ratios up to (L3 % + N1 %), which had the highest strength. Beyond this ratio, slight fluctuations were observed, while total suction continued to decrease. This is likely due to nanoparticle agglomeration at excessive treatment levels, reducing soil cohesion. In SG2 % soil, compressive strength showed fluctuations, initially increasing, then decreasing until stabilization, while total suction was consistently reduced. The lower suction values in SG2 % soil compared to SG50 % are attributed to its lower gypsum content, which reduces chemical reactions with water and the formation of suction-enhancing compounds.

Keywords: Gypsum Soil; Compressive Strength; Suction; Lime; CaCO3 Nanoparticles.

RESUMEN

Este estudio examina las características y la estabilización de dos tipos de suelos de yeso, conocidos por su alto contenido en yeso, que afecta a sus propiedades físicas y químicas. Los suelos de yeso plantean desafíos en la construcción debido a su solubilidad en agua, lo que conduce a la inestabilidad. La investigación se centra en la interacción del contenido de humedad, la concentración de yeso y la estructura del suelo en diferentes condiciones climáticas.
El estudio evalúa la relación entre la succión total del suelo, medida mediante el método del papel de filtro, y la resistencia a la compresión no confinada en suelos de yeso naturales y procesados. Se exploraron técnicas de estabilización utilizando CaCO3 y nanopartículas (NPs) de cal. La conexión entre la resistencia a la compresión y la succión total se estableció mediante el grado de saturación obtenido a partir de la curva característica del agua del suelo y el contenido óptimo de agua.
Los resultados mostraron que para el suelo SG50, la resistencia máxima a la compresión aumentaba con las proporciones de tratamiento hasta (L3 % + N1 %), que presentaba la mayor resistencia. Más allá de esta

relación, se observaron ligeras fluctuaciones, mientras que la succión total siguió disminuyendo. Esto se debe probablemente a la aglomeración de nanopartículas en niveles de tratamiento excesivos, lo que reduce la cohesión del suelo. En el suelo SG2 %, la resistencia a la compresión mostró fluctuaciones, aumentando inicialmente y disminuyendo después hasta la estabilización, mientras que la succión total se redujo de forma constante. Los menores valores de succión en el suelo SG2 % en comparación con el SG50 % se atribuyen a su menor contenido en yeso, que reduce las reacciones químicas con el agua y la formación de compuestos potenciadores de la succión.

Palabras clave: Suelo de Yeso; Resistencia a la Compresión; Succión; Cal; Nanopartículas de CaCO3.

INTRODUCTION

Common in arid and semi-arid areas, such as Spain, the Middle East, and parts of Australia, unsaturated gypsum soils—have high gypsum content which greatly influences their physical and mechanical behavior. The combination of voids or air pockets defining such soils impacts their mechanical characteristics and stability. The problematic nature regarding unsaturated gypsum soils in construction as well as geotechnical engineering is one of the main reasons one studies them. Their sensitivity to dissolution in water might cause ground subsidence and collapses, so presenting major difficulties for land management and the development of infrastructure. Effective design and construction methods depend on an understanding of such soils to guarantee the longevity and safety of constructions built within or on them.[1]

The special qualities of unsaturated gypsum soils, like low compressibility under unsaturated conditions and high collapse potential when wet, provide major technical difficulties. Those soils have a complicated interaction among gypsum content, moisture content, and soil structure that could cause unpredictable behavior depending on the environmental conditions. Dealing with such difficulties calls for innovative solutions and stabilization methods such cement kiln dust (CKD), which increases the mechanical qualities of the soil and lowers its collapse susceptibility. Development of efficient management methods and engineering solutions to reduce the hazards related with unsaturated gypsum soils depends on advanced research and studies, thereby guaranteeing safe and sustainable construction practices in the impacted areas.[2]

The objective of this study is to investigate the relation between unconfined compression strength in unsaturated gypsum soils utilized in this work in both processed and natural forms and soil total suction assessed using the filter paper approach. The soil treatment includes two stages with two treatment materials, namely lime and calcium carbonate nanoparticles, in the first stage, the treatment is carried out with 4 % (L4 %) of lime as the first treatment ratio and then replacing (0,25,0,5 and 1) % proportion of lime with calcium carbonate nanomaterial CaCO3 to make the treatment ratios as follows:

- (L3,75 % + N0,25 %) = 3,75 % lime + 0,25 % Nano
- (L3,5 % + N0,5 %) = 3,5 % lime + 0,5 % Nano
- (L3 % + N1 %) = 3 % lime + 1 % Nano

Followed by the second stage of treatment with 8 % lime (L8 %), and then part of the percentage of this material is replaced with calcium carbonate nanoparticles (CaCO3) in the proportion as in the first stage and as follows:

- (L7,75 % + N0,25 %) = 7,75 % lime + 0,25 % Nano
- (L7,5 % + N0,5 %) = 7,5 % lime + 0,5 % Nano
- (L7 % + N1 %) = 7 % lime + 1 % Nano

The importance to be reached through this relationship is to know the extent of total suction of gypsum soils of the two types used in this research (50 % & 2 % gypsum content) when using the optimum water content in the preparation of an unconfined compression test, this is done by the characteristics curve of soil water extracted from filter paper method between the saturation degrees and total suction values of this soils.

Literature Review

Short- and Long-Term Effects of Lime and Gypsum Applications on Acid Soils

This review discusses the combined use regarding gypsum and lime on soil chemical properties, including their impact on soil acidity and aluminum toxicity. It is published in Agronomy.[1]

Collapse and Volume Change of Unsaturated Gypseous Soil: A Model Study

With an emphasis on suction, vertical stress, and collapse potential, this research investigates how wetting affects gypseous soil. Additionally, it looks into how capillary rise as well as water volume penetration are affected by the amount of gypsum present.[3]

Soil Stabilization Using Gypsum and The Effect Based on The Unconfined Compressive Strength Values

This study concentrates on the impact regarding gypsum as a soil stabilizer and its impact on unconfined compressive strength.(4)

Unsaturated Conditions of Gypsum Sand Soils and Its Improvement with CKD Material

Results on the effect of matric suction on the compressibility related to unsaturated gypsum sand soil are presented in this conference paper. The International Conference on the Geo-technical Engineering's conference proceedings contain it.(2)

Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper (ASTM D5298-16)

Using filter paper as a passive sensor to evaluate the soil matric and suction potential is covered by this standard test procedure. In order to assess soil matric and total potential, it offers a method for calibrating several kinds of filter paper.(5)

Effect of Suction on Unconfined Compressive Strength of Clayey Soils

The impact of matric suction on the unconfined compressive strength of clayey soils with varying sand concentrations is examined in the present work. The findings indicate that, up to a certain limit, unconfined compressive strength rises as matric suction increases.(6)

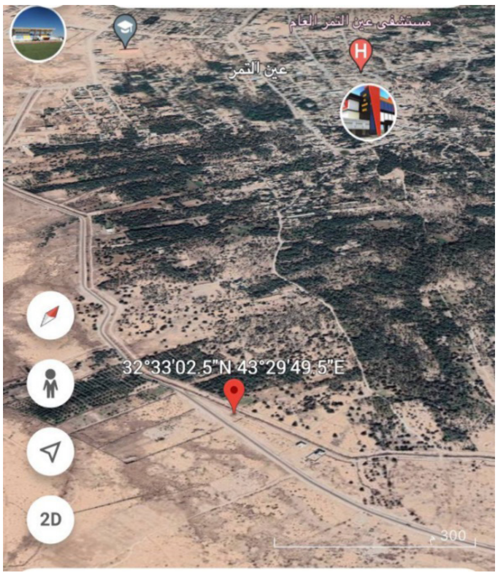
METHOD

Soil Samples

Samples have been collected from two distinct areas: the Shabas Salman area in Hindi District of the Karbala governorate, and Ain Al-Tamr area, which is 40 kilometers west of Karbala city. With a gypsum content of up to 50 % of its weight, the first soil type - which comes from the Ain Al-Tamr district as depicted in figure 1 is categorized as belonging to extremely high gypsiferous soils and can be labeled as SG50. The second kind, which will be labeled SG2 as seen in figure 2, came from the Shabas Salman region and had a gypsum content of roughly 2 % of its weight, placing it into the category of soils with a relatively low level of gypsum. The table below exhibits the characteristics of each of the two types of soil used for this research

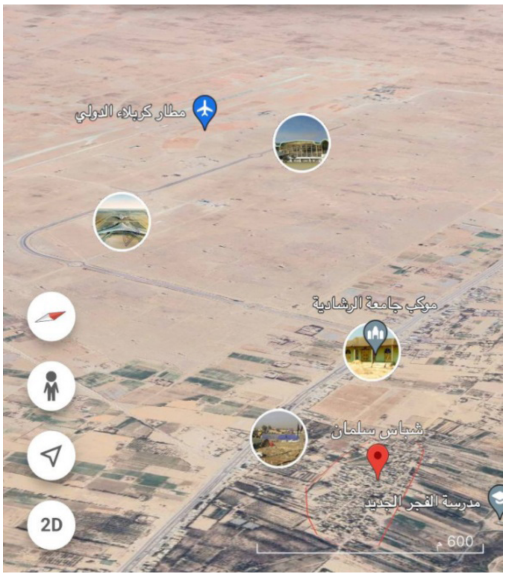
Table 1. Characteristics of SG50 % & SG2 %

Soil type	**SG50**	**SG2**
Classification	SP	SP
Gypsum content	50 %	2 %
Barazanji classification	Very high gypsiferous	Relatively low gypsum
Specific gravity	2,52	2,74
Void ratio	0,625	0,38
Optimum moisture content	19,4 %	8,5 %



Source: Google Earth

Figure 1. Location of SG50



Source: Google Earth
Figure 2. Location of SG2

Soil Treatment

The method used to treat gypsum soils of the two types used in this research included treatment using slaked lime and then replacing part of the lime treatment ratios with calcium carbonate nanoparticles CaCo3. the following is an explanation of the performance of each of them in the treatment:

Treatment with lime

A common method for improving the engineering characteristics of gypsum-rich soils and lessening the challenges caused by an excessive gypsum concentration is lime treatment. The reaction regarding lime with gypsum and other soil elements changes the structure, chemistry, and behavior of the soil. Quicklime (calcium oxide) and hydrated lime (calcium hydroxide) are the two most frequent forms of lime. It is essential to consider factors such lime dosage, soil moisture content, mixing methods, and curing time when applying lime for the chemical treatment of gypsum soils in order to get the desired soil benefits. Appropriate soil testing, engineering design, and laboratory analysis are necessary to effectively stabilize soil for construction projects and choose the optimal lime treatment scheme.[7]

Treatment with calcium carbonate nanoparticle

Applying CaCo3 NPs (nano-calcium carbonate) to gypsum-rich soils is a practical way to improve soil properties and deal with the challenges brought on by high gypsum levels. A far greater surface area is produced when calcium carbonate is produced at the nanoscale. The reactivity regarding sodic soils will be enhanced by the nanomaterials' larger surface area, which will accelerate the rate of soil amendment. The interaction of CaCo3 nanomaterials in trace amounts with gypsum ($CaSO_4 \cdot 2H_2O$) has not been reported in any publication. Recovery of sodic soils is expected to benefit from the long-term use of this CaCo3-nano material. In particular, the problems with sodic soils will be successfully and efficiently addressed with nanomaterials. Benefits of this include accelerating the reaction rate and using less material to treat sodic soils, which will reduce the amount of physical ameliorant used and the area excavated for mixing.[8]

Filter Paper Method

This method has been carried out according to ASTM D5298,[9] Whatman filter paper No. 42, and its calibration curve was used in contact as well as non-contact techniques for the measurement of matric suction and total suction, respectively. The samples were prepared at room temperature, where the dry filter papers were extracted from their boxes and processed and handled using tweezers and gloves to ensure they were not contaminated. The examination was carried out for a group of samples, which included the natural state of each soil, in addition to the stated treatment ratios for each soil with optimum moisture contents and different densities depending on the previously applied compaction test results for each sample and in five degrees of saturation % (10, 30, 50, 70, 90) for each test sample for providing a range of suctions for measurements.

The filter paper must be positioned in a non-contact manner with the soil in order to use the total suction approach. The following is a description of a testing procedure for total suction measurements with the use of filter paper:

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Soil Total Suction Measurements

- For each degree of saturation of each test for one of the treatment percent and un-treated state, two PVC rings with a diameter of 6,80cm and a height of 3,0cm are equipped for each test to bring the sample weight according to the size of the ring and the density of soil with the optimum moisture content and mixed to be stacked in the form of three layers, each layer is stacked with a thickness of 1 cm (10,0mm) inside each ring.
- In the same way, with the accuracy and speed possible, compaction is carried out in the second ring, taking into account the preservation of the moisture of the first ring after compaction as much as possible.
- The two rings are placed tightly wrapped together with plastic tape inside a sealed glass jar with a diameter of 8,0cm and a height of 12,0cm to occupy their volume of approximately 75 % of the volume of the jar (taking into account the possible speed of performance to avoid loss of sample moisture)
- After the sample is inserted into the jar, an annular support with a diameter smaller than the diameter of the filter paper and a height of approximately 1,5 cm is placed directly on the soil surface to prevent any contact between the soil and filter paper.
- With tweezers, the filter paper is carefully placed on top of this support, stressing that it should not come into contact with the soil or the inside of the jar, and also making sure that the material made of this ring support is plastic or glass to prevent its corrosion during the examination.
- The jar’s lid is closed and very tightly tied with plastic tape
- These steps are repeated for each degree of saturation within each suction check.
- After that, the glass jars are placed in an ice box and in a room with a controlled temperature to reach the necessary time for equilibrium.
- Researchers suggest a minimum equilibrating period of the sandy soil is 7 days.[9,10,11]
- These steps are documented in photographs in figure 3.

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Figure 3. Steps of conducting total suction by filter paper

- When the equilibrium state of the sandy soil is reached, the glass containers are extracted from the room adapted to maintain the temperature, and the aluminum cans used for moisture content calculations are weighted to the nearest 0,0001 gm.
- The glass container is opened and it is preferable to have another person put the filter paper using tweezers in the aluminum can and lid it in less than a few seconds as possible.
- The weight of each Aluminum Can is taken with the wet filter paper inside and also at an instantaneous speed. After that, the weight is recorded in the data sheet prepared for examination.
- The above two steps are done for each glass container, then the aluminum cans with their half-open lids and wet filter paper inside are placed in the oven to allow them to evaporate and remain for at least 10 hours at a temperature of 110 ± 5 degrees Celsius as shown in figure 3.
- After that, the cans are taken out of the oven after being covered with their lids to allow them to balance for 5 minutes and then placed on a block of aluminum to be cooled for about 15 seconds.
- Each Aluminum Can is weighed with a dry filter paper inside and the weights are recorded, after which the filter paper is extracted quickly and the weight of the Can is empty so that the difference between the two weights is the weight of the dry filter paper and is denoted by the symbol M2t if the filter paper is for total suction.
- From the difference between the weight of the can with the wet filter paper inside and its weight when it is empty, the weight of the wet filter paper is extracted and denoted by the symbol M2t.
- Through the difference between the two weights, the weight of the water absorbed by the filter paper is extracted, and by dividing by the dry weight of the filter paper, the water content of the filter paper is extracted for the total suction measurements.
- The recorded readings of all samples are taken and fixed on a special sheet for each sample examination. Then the curves of soil water characteristics are deduced.
- Finally, the total suction corresponding to these degrees of saturation is extracted by using the extracted water content of the filter paper for each degree of saturation and the calibration curve assigned to the Whatman 42 paper. Then the soil water characteristic curve is obtained for both soil types in each treated ratio and untreated state.

Unconfined Compression Test UCT

The test was carried out on the two types of soil used in this research with the mentioned treatment percent for each of them and with a 7-day curing case for each treatment percent. The curves of UCT for SG50 & SG2 curing periods of 7 days are shown in the figures 4 and 5.

The ASTM D 2166 guidelines[12] were followed in doing this test, which included meticulously trimming the soil to the appropriate dimensions. Each sample was prepared with the maximum dry density and optimal water content according to the desired percent and placed in a cylindrical mold with dimensions of 67*38 mm with a height-to-diameter percent of about 2:1 as shown in figure 6. After painting the mold with Greeze Oil, tightening the screws and stacking it with the appropriate tool, and then placing them in the Iron Cap to compress it with a load force of up to 100 Kpa after that, the screws are opened, extracted the sample, recorded its dimensions, wrapped it with a nylon bag, and then coded by the processing ratio, date and period necessary for curing as shown in the figure 7 below. When the samples complete 7 days of curing, they are extracted and placed in an un-confined compression testing machine where applied Axial load at a constant rate is usually 0,5 mm/min, and according to the standards of ASTM,[12] the load is increased until the sample fails, which is indicated by a noticeable decrease in load versus an increase in stress.

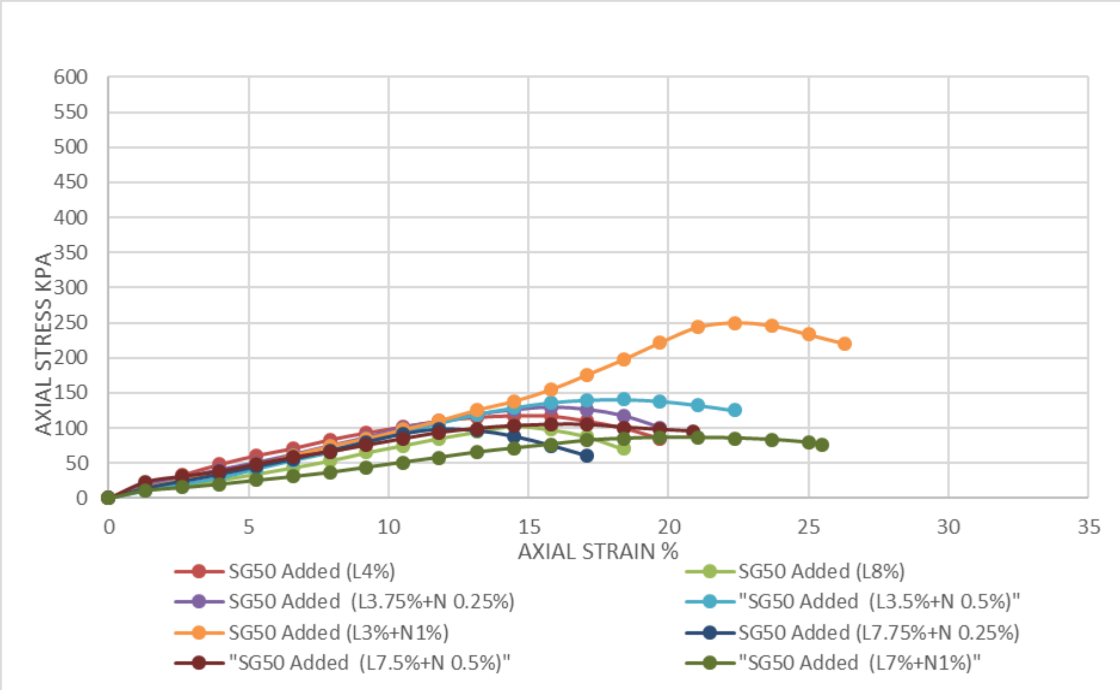

Figure 4. UCT for SG50 curing 7 days

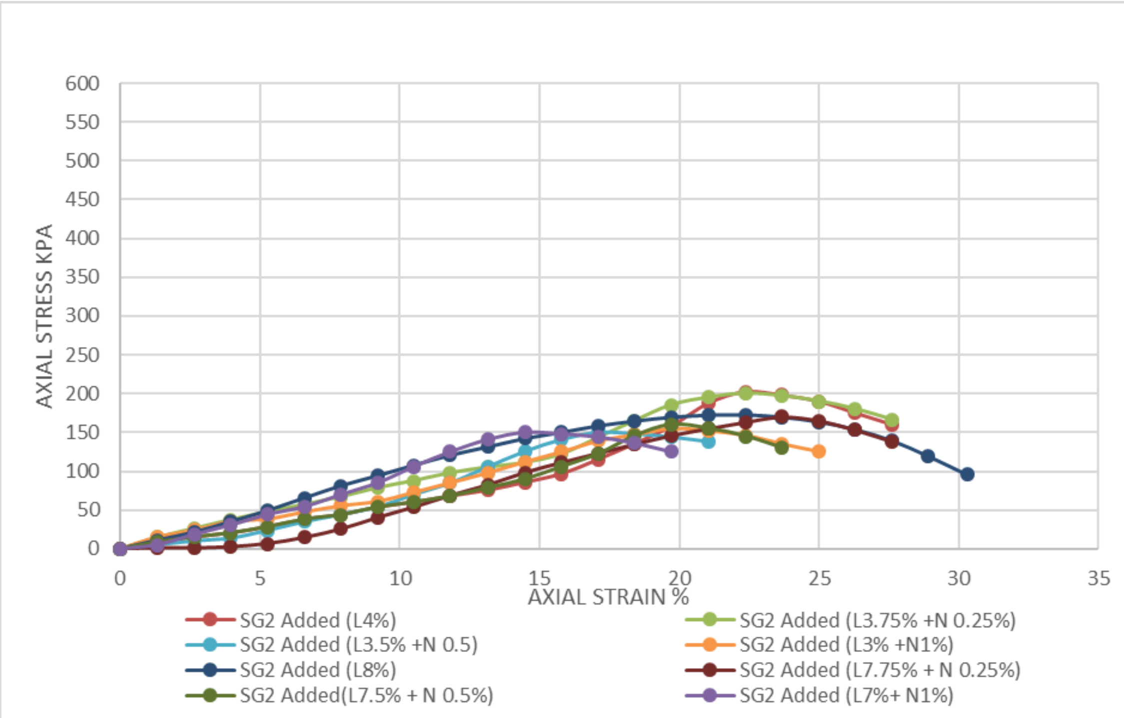

Figure 5. UCT for SG2 curing 7 days

Throughout the test, data on the axial load and corresponding deformations are recorded. The unconfined compressive strength is calculated as the maximum axial stress the specimen can withstand. This value is crucial for various geotechnical engineering applications, such as the stability analysis of foundations, retaining walls, slopes, and embankments. The UCT provides a rough estimate of soil strength, which is essential for determining appropriate construction techniques and ensuring the safety and stability of engineering projects.

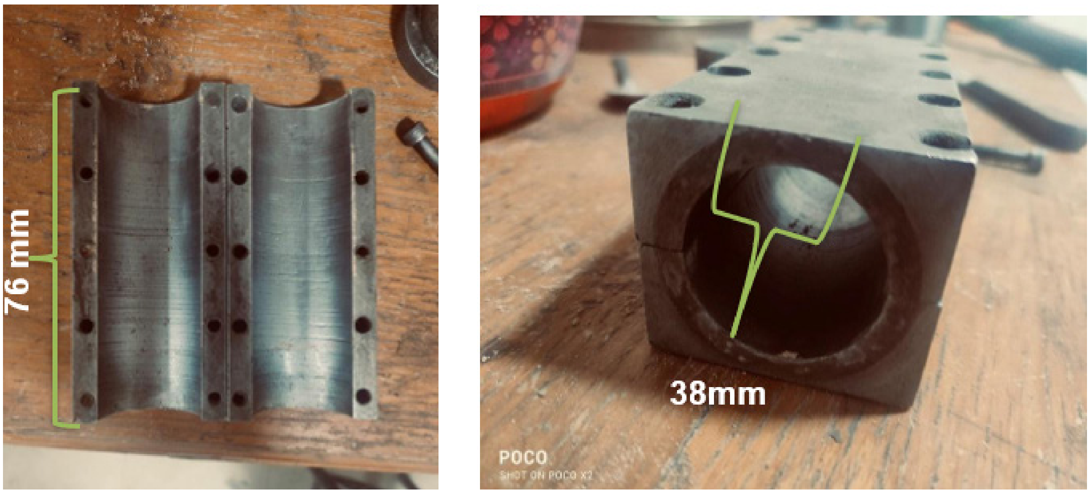

Figure 6. Dimensions of the UCT mold

Figure 7. Steps for conducting a compressive strength test

Data Analysis

After finding the total suction values using the filter paper's calibration curve and the filter paper's water content at each degree of saturation, the soil water characteristic curve (SWCC) is obtained.

The relationship between the SWCC for the two types of soils (in their natural state and all treatment ratios) and the results of compression strength at the curing 7 days was based on the optimal moisture content used in the preparation of compression test samples, which was obtained from conducting a modified soil compaction test, whereby the void ratio and specific gravity, the saturation degree of each water content is extracted for soils whether in its natural or treated State and then by the suction value corresponding to this saturation degree is determined on the soil water characteristic curve extracted from the results of the filter paper method, and thus comparing these suction results with the results of compressive strength obtained for the curing stage (7) days and find out to what extent the total suction in each type of soil with their treatment ratios can affect the compressive strength at this age of curing.

RESULTS

The following are the curves of the soil water characteristics for both types of soil used SG50 and SG2, by and using the ratios of the degrees of saturation obtained from the optimal water content ratios when preparing samples of unconfined compression test.

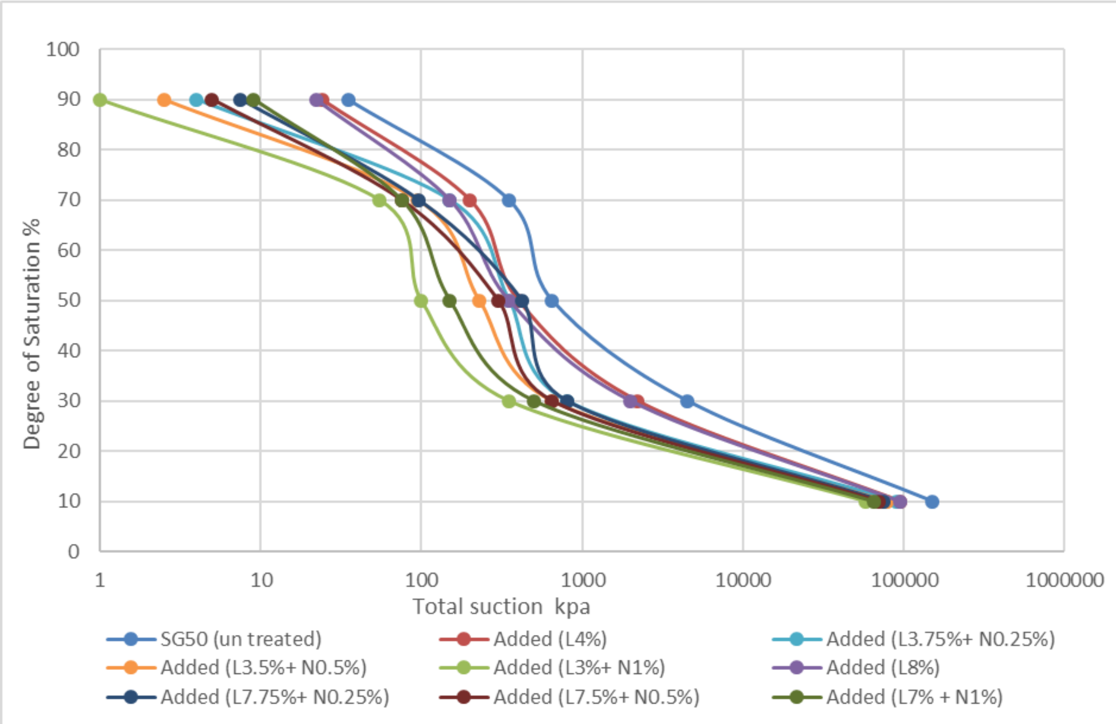

Figure 8. Total suction of SG50 %

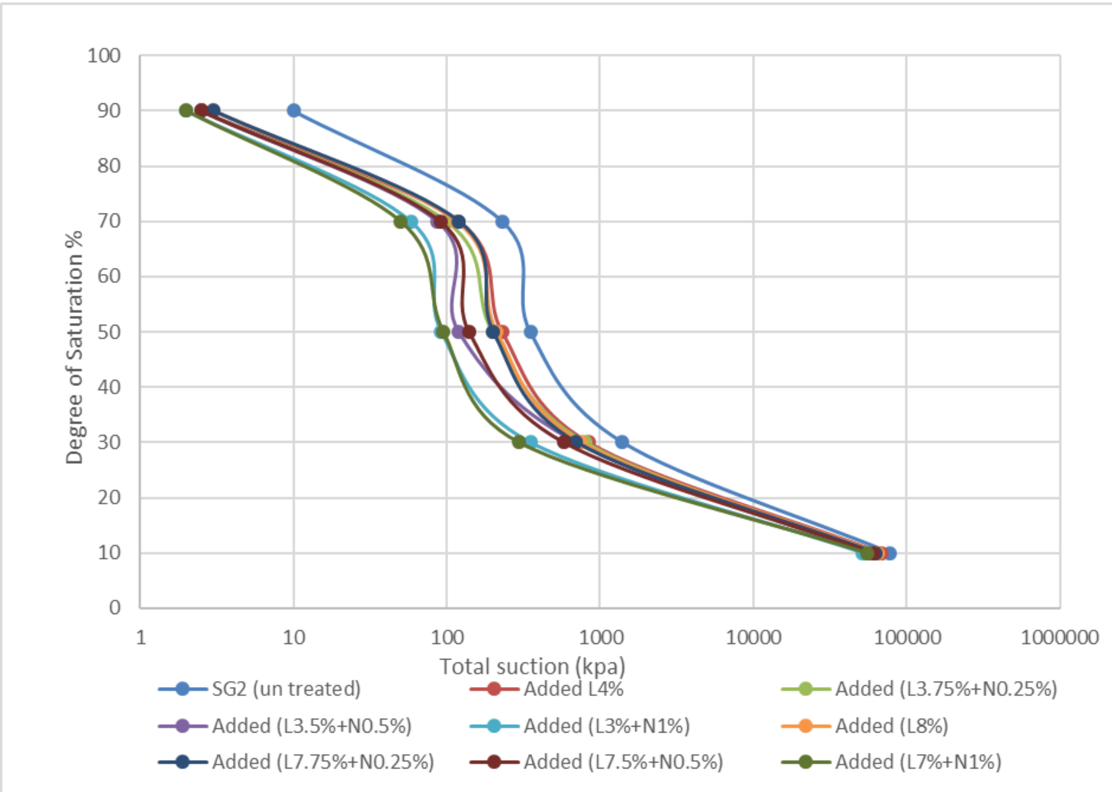

Figure 9. Total suction of SG2 %

Through the above curves in figures 8 and 9, the total suction values corresponding to the saturation degrees for each of the treatments mentioned above ratios for both soils are extracted, as shown in table 2 and table 3:

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Table 2. Calculations total suction & UCS of SG50 %

Treatment ratio %	SG50 Total suction Kpa	SG50 Max. Unconfined compressive strength during 7 days
Natural state	221	45 (un curing)
L4 %	200,9	117,6
L3,75 %+N0,25 %	180	129,6
L3,5 %+N0,5 %	165	140,4
L3 %+N1 %	150	250
L8 %	190	102
L7,75 %+N0,25 %	175	98
L7,5 %+N0,5 %	160	104,8
L7 %+N1 %	145	86,6

Table 3. Calculations total suction & UCS of SG2 %

Treatment ratio %	SG2 % Total suction Kpa	SG2 % Max. Unconfined compressive strength during 7 days
Natural state	150	93) un curing)
L4 %	112	202,6
L3,75 %+N0,25 %	70	200
L3,5 %+N0,5 %	92	150
L3 %+N1 %	63,7	150
L8 %	100	172,63
L7,75 %+N0,25 %	75,8	170
L7,5 %+N0,5 %	57,8	160
L7 %+N1 %	33	150

The results show that for SG50, total suction continued to decrease as the maximum compressive strengths increased with the treatment ratios, up to the (L3 % + N1 %) treatment ratio, which had the highest compressive strength. However, beyond this ratio, the treatment percentages showed slight fluctuations, either decreasing or slightly increasing the maximum compressive strengths, while total suction values continued to clearly decrease. This can be attributed to the fact that if the treatment materials are not evenly distributed or are used in quantities larger than beneficial, agglomeration of nanoparticles can occur, reducing the mechanical cohesion of the soil structure and consequently its compressive strength. Figure 10 illustrates the development of compressive strength for treatment ratios along with total suction.

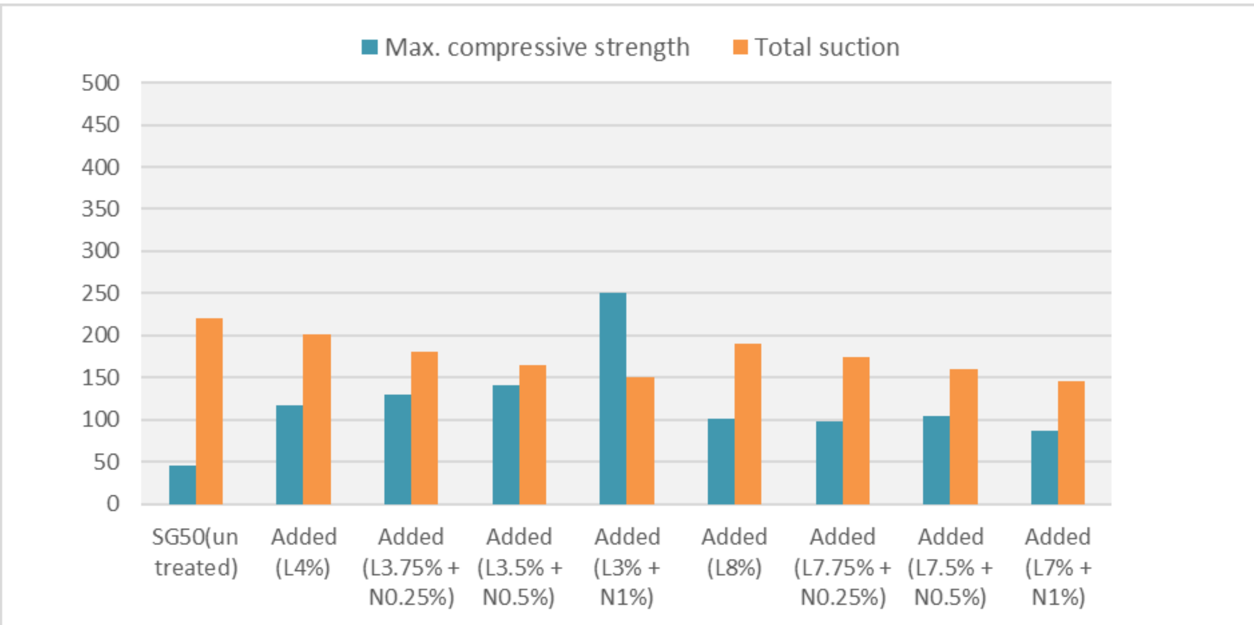

Figure 10. USC & Total suction for soil SG50

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In SG2 % soil, the results showed fluctuations in compressive strengths between treatment ratios, where there was an initial increase in the early stages of treatment, followed by a decrease until it nearly stabilized, coinciding with the continued decrease in total suction throughout the treatment phase this result can be explained as a consequence of simultaneous effects, where an initial improvement in soil strength occurs due to interaction with the treatment materials, followed by negative effects caused by uneven distribution, decreased suction, and potential particle agglomeration when excessive amounts are used. , as shown in figure 11. It was observed that the total suction results, for this soil were lower than those of the SG50 % soil, as this soil has a lower gypsum content, making its suction capacity lower, which reduces the chemical reactions between gypsum and water and consequently decreases the formation of pathways and compounds that contribute to increased water suction.

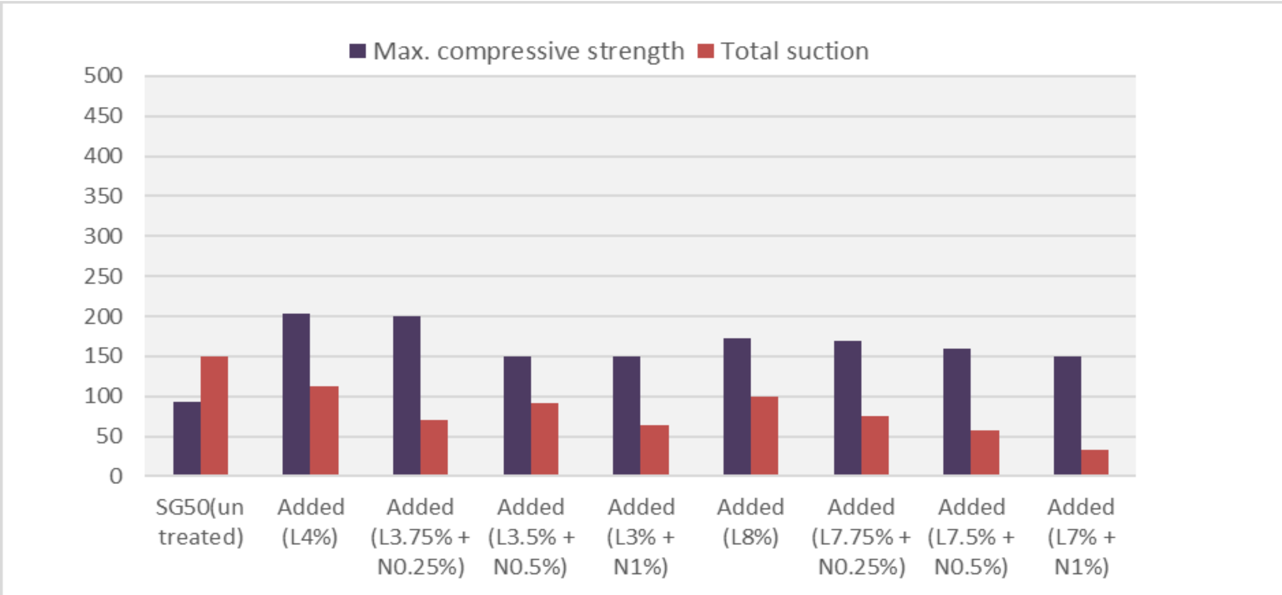

Figure 11. USC & Total suction for soil SG2 %

CONCLUSIONS

The study of gypsum soils with varying gypsum content, their behavior under different moisture conditions, and their treatment with lime and calcium carbonate nanoparticles provided key insights into soil engineering. Soils with lower gypsum content (2 %) generally exhibited higher compressive strength and greater water suction capacity than those with higher gypsum content (50 %). Treatment with lime and $CaCO_3$ nanoparticles enhanced cohesion, reduced porosity, and improved structural stability, increasing compressive strength in SG50 soil up to a ratio of 3 % lime and 1 % nano $CaCO_3$. Beyond this, strength gradually decreased due to excessive chemical reactions with gypsum components, reducing compressive strength.

In contrast, SG2 % soil showed an initial increase in compressive strength, followed by fluctuations. Despite initial improvement from treatment, uneven material distribution negatively impacted soil cohesion, forming weak zones and reducing strength. Additionally, excessive treatment led to nanoparticle agglomeration, further weakening the soil.

Understanding the interaction between soil suction and compressive strength in treated and untreated gypsum soils was crucial for developing effective stabilization techniques and ensuring the structural integrity of constructions on such soils. These findings highlight the importance of tailored treatment strategies for optimal geotechnical performance.

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Methodology: Sarah Al-khafaji, Ahmed Al-Janabi.
Software: Sarah Al-khafaji, Ahmed Al-Janabi.
Drafting - original draft: Sarah Al-khafaji, Ahmed Al-Janabi.
Writing - proofreading and editing: Sarah Al-khafaji, Ahmed Al-Janabi.