



Studying Characteristics and Strength of the Unsaturated Gypseous Soil with Various Saturation Degrees

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HIGHLIGHTS

- Tests on gypseous soil include standard Proctor compactions and consolidated undrained triaxial compression.
- The soil was either natural, unsaturated at degrees of saturation (30%, 60%, and 80%), or fully saturated.
- Increasing the humidity of the gypseous soil at saturation degrees causes a decline in the internal friction angle.
- The soil cohesion for effective and total stress increased with gypseous soil moisture up to (60%) saturation degree.

ARTICLE INFO

Handling editor: Mahmoud S. Al-Khafaji

Keywords:

Characteristics
Gypseous soil
Various saturation degrees
Strength
Unsaturated

ABSTRACT

The main objective of this study is to determine the appropriateness of unsaturated gypseous soil as a subgrade layer for carrying foundations. A comprehensive laboratory testing program was implemented to investigate the geotechnical characteristics and behavior of unsaturated gypseous soil. Tests that are physical included specific gravity, classification tests, relative density, Proctor compactions, single and double oedometer collapse potential, and static triaxial compression (CU-test). Chemical testing, Scanning Electron Microscopy (SEM), and Electronic Dissipation x-ray Scanning (EDS) analyses were also carried out. The tests were performed for samples prepared at 70% relative density of the natural gypseous soil. Tests are performed on the natural, unsaturated at degrees of saturation (30%, 60%, and 80%) and fully saturated gypseous soil to investigate the gypseous soil behaviors. In both single and double oedometer testing, it was discovered that the degree of specimen collapse is (Moderate) at 70% relative density, with a collapse index value ranging from (4%). The angle of internal friction for both total and effective stresses (ϕ' and ϕ) decreases as the moisture content of the gypseous soil increases at all saturation levels. In contrast, it was found that the strength of soil cohesion for both total and effective stresses (c' and c) increased with increasing gypseous soil moisture up to saturation (60%), which led to a rise in soil shear strength. The reduction value ranged from (38.50° to 7°) in respect of effective stresses and between (34.50° and 7°) with respect to total stresses. Effective stress increase varied from (10.0 – 26.0 kPa), and total stress increase ranged from (12.50 – 28.0 kPa). Then the strength started gradually decreasing at the saturation degrees 80 and 100%, respectively. As a result, the shear strength of the soil decreases with the value of reduction ranging from (20.0 – 11.50 kPa) for effective stresses and (21.50 – 11.50 kPa) for total stresses.

1. Introduction

Gypseous soils are unsaturated soils that cover the bulk of the land's surface or near surface. According to Fredlund and Rahardjo [1] unsaturated soil is often referred to as a three-phase system, with these phases being (air, water, and solid). On the other hand, the study of gypseous soils for many years has attracted the attention of many scientists. Gypseous soil is a collapsible soil, which is defined as unstable soil with grain rearrangement, its size decreases mainly when soaked with water under the effect of loads applied on it or without the addition of any load [2,3]. Knowing the behavior of unsaturated gypseous soils will become more important in the future as a result of global warming forecasts, which are projected to result in a decrease in the groundwater level and hence a rise in the worldwide distribution of unsaturated gypseous soils.

There is great importance to the identification of engineering geotechnics and geologies problems with problematic gypseous soils. In general, the gypsum element is stable because of the two water bonds, as shown in the chemical formula ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) [4]. The gypsum-rich soil covers a significant region around the Middle East, including much of Iraq [5]. In addition, sudden collapse can occur in gypseous soil upon wetting [6]. There is an imperative need to study and look into the characteristics of unsaturated gypseous soil because the available information is a severe lake in the Middle East in general and in Iraq in particular, whenever the gypseous soil is in its natural state or is dry, and the process of soaking has begun with or without additional load

on the soil. Whereas in the case of drought, the gypsum elements operate as bindings between soil particles, yet as saturation increases, these ties are destroyed and the soil deforms significantly. Therefore, some important tests such as oedometer and triaxial tests were compared by many researchers to collapsing, gypseous, and unsaturated soils during the past years. Many previous investigations have looked into the effect of gypsum content on various soil characteristics. Researchers investigated the influence of gypsum concentration on soil shear strength for several soil samples at different locations in Iraq [7-10], whereas other researchers [11-18] studied the soil deformation caused by various processes. All of these studies claimed that when the gypsum content increased, the shear strength decreased and the strains increased. The existence of gypseous soils in the pavement subgrades causes serious problems to the pavement, as they undergo a reversible swell–shrink behavior [19]. The swell–shrink behavior is partly due to the dissolution of gypsum and partly due to the expansion of soil particles upon the water flow, both of which induce volume increase and strength reduction [20]. Therefore, the construction of engineering structures upon such soils can be harmful, as they induce a severe challenge, threatening sustainability by inducing ground subsidence with the formation of voids, cracks, excessive settlement in dry conditions, and volume expansion upon wetting [21,22].

In general, many problems appear in gypseous soils whenever this soil becomes saturated by moisture as a consequence of gypsum breakdown or immersion, which leads to the structure collapse due to cracking and sloping [7]. Whereas, when sedimentation occurs in wet soil or groundwater, the fundamental issue is when the gypsum component starts dissolving with water, causing the bond between soil particles to break down.

This study aims to determine the appropriateness of unsaturated gypseous soil as a building material. Furthermore, such an objective is thought to be useful in evaluating appropriate methods to investigate the features and behaviors of unsaturated gypseous soils, such as shear strength under various saturation degrees. Studying the change in shear strength parameters of gypseous soil upon wetting is very important.

2. Experimental Works

2.1 Soil Characteristics

This study utilizes sandy gypseous collapsible soil obtained from Tikrit, Salah Al-Dean government, for analysis. A series of routine experiments was conducted to determine the physical properties of the soil. Table 1 provides detailed information on the physical parameters of the soil used. The particle size distribution is illustrated in Figure 1, indicating that the gypseous soil sample consists mostly of sand with some fines (silt and clay), and a minimal amount of gravel. Figure 2 shows the dry density and moisture content obtained from the Proctor standard test. Additionally, chemical properties of the soil were evaluated through a standard series of tests. Some of these tests were conducted in the Soil Mechanics Laboratory, while others were carried out in the Sanitary and Environmental Laboratory of the Department of Civil Engineering at the University of Technology. Table 2 provides detailed information on the chemical characteristics of the soil used.

Two methods are used to measure the gypsum content in the soil:

A. Nashat and Al-Mufti method:

This method was proposed by Nashat and Al-Mufti [31], to measure the gypsum content in the soil (χ). It depends on heating the gypsum salt between the soil grains, and it is in two stages. First stage, the water is expelled from the soil particles by placing the gypsum soil sample in the oven at a temperature of (45)°C for several days until the weight of the soil becomes constant ($w_{45^\circ\text{C}}$). Then in the second stage, the gypsum is heated by placing the soil sample in the oven at a temperature of (105)°C for (24) hours ($w_{105^\circ\text{C}}$), then the gypsum content is calculated according to Equation 1.

$$\chi = \frac{w_{45^\circ\text{C}} - w_{105^\circ\text{C}}}{w_{45^\circ\text{C}}} \times 4.7778 \times 100 \quad (1)$$

where: χ = Gypsum content by weight (%), $w_{45^\circ\text{C}}$ = Weight of sample at (45)°C, $w_{105^\circ\text{C}}$ = Weight of sample at (105)°C, and 4.7778 = Inverse proportion of hydration water molecular weight to gypsum molecular weight.

B. Approximate method:

This method depends on the percentage of total sulphate content in the soil (SO_3), which the gypsum content (χ) is calculated according to British Standard [32].

$$\chi = \text{SO}_3 \times 2.15 \quad (2)$$

where: χ = Gypsum content by weight (%), SO_3 = Total sulphate content, and 2.15 = Inverse proportion of hydration water molecular weight to gypsum molecular weight.

Table 1: A summary results of the physical characteristics of used gypseous soil

Characteristic		Value	Ref.
Specific gravity	G_s	2.43	[23]
Water content	$w_c, \%$	1.59	[24]
Atterberg limits	PL, %	16	[25]
	LL, %	20	
	PI, %	4	
Particle size distribution by wet sieving, (%)	Gravel	1	[26]
	Sand	79	
	Fines	20	
Soil classification	U.S.C.S	S.M	[27]
Max. dry density (gm/cm ³)	$\rho_{d \max}$	1.71	[28]
	e_{\min}	0.42	
Min. dry density (gm/cm ³)	$\rho_{d \min}$	1.20	[29]
	e_{\max}	1.03	
Proctor's compaction (Standard method)	O.M.C, (%)	13.0	[30]
	$\rho_{d \max}$, (gm/cm ³)	1.71	

Table 2: A summary of results of the chemical features of used gypseous soil

Characteristic	Value	Ref.
Gypsum content (CaSO ₄), (χ), %	44.70	[31]
	45.30	[32]
Total sulphate content (SO ₃), %	21.07	[32]
Carbonate content (CaCO ₃), %	22.50	[32]
Total dissolved salts (TDS), ppm	1214.0	[32]
Total soluble salts (TSS), %	40.10	[32]
pH value, (pH)	7.230	[32]
Organic matters (O.M), %	0.720	[32]
Chloride content (Cl ⁻¹), ppm	370.0	[32]
Conductivity (E _c), μ S	1837.0	[32]

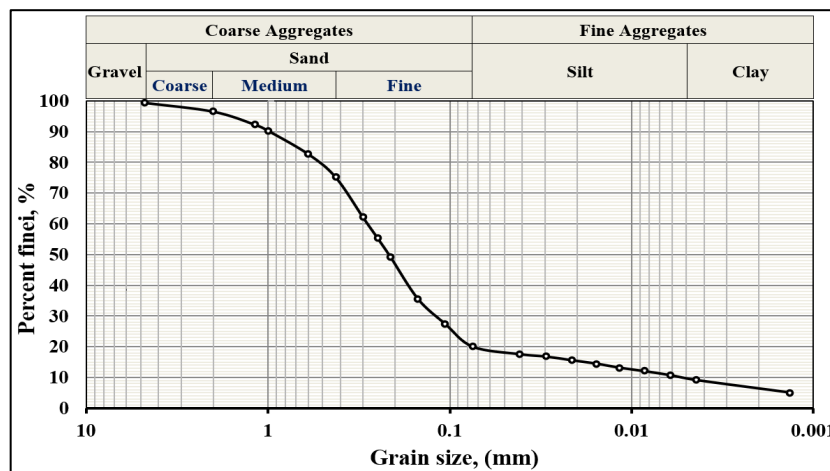


Figure 1: Curve of particle size distribution of the utilized gypseous soil

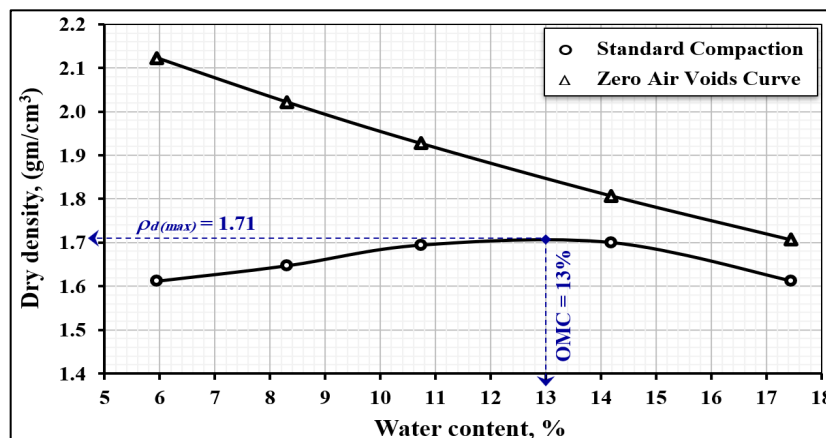


Figure 2: Gypseous soil Proctor standard compaction curves

2.2 Mineralogical Analysis

The microparticle minerals present in the gypsum soils were detected at the Department of Applied Sciences, University of Technology, using Scanning Electron Microscopy (SEM) and Electronic Dissipation X-ray scanning (EDS) to analyze the mineralogy of the soil particles.

2.3 Collapse Tests

Collapsibility is a characteristic observed in loose, low-plasticity, unsaturated soils. To confirm the behaviors and properties of gypseous soils, several tests are performed, including the Single Oedometer Test (SOT) as per ASTM D5333 [33], and the Double Oedometer Test (DOT). The testing program used a relative density (D_r) of 70% for the gypseous soil. The following tests were conducted:

- One test of the Single Oedometer Test (SOT).
- Two tests of the Double Oedometer Test (DOT).

2.3.1 Single oedometer test (SOT)

This test follows the specifications outlined in ASTM D5333 [33] to determine the soil collapse potential. The soil was prepared in an oedometer mold with a specified relative density of 70%. The test was conducted under the soil's initial conditions until a stress of 200 kPa was reached. Subsequently, the sample was soaked in water for 24 hours. The collapse potential (C_p , or I_c), and collapse index (I_e) are calculated by using Equation 3. The classification of collapse index (I_e) for any soil is listed in Table 3 according to ASTM [29].

$$I_c = C_p = \left(\frac{\Delta e}{1 + e_o} \times 100 \right) = \left(\frac{\Delta h}{h_o} \times 100 \right) = I_e \quad (3)$$

where:

I_c , C_p = Collapse potential. At any stress level, the relative magnitude of soil collapse is determined as a percentage,

I_e = Collapse index. At 200 kPa, the relative size of the collapse was calculated as a percentage,

Δe = Change in void ratio resulting from wetting (collapse strain),

e_o = Initial void ratio,

h_o = Initial height of the specimen (mm), and

Δh = Change in the height of specimen as a result of wetting (mm).

Table 3: Classification of the collapse index (I_e) [33]

Collapse Index (I_e), %	Degree of Specimen Collapse
0	None
0.1 – 2	Slight
2.1 – 6.0	Moderate
6.1 – 10	Moderately Severe
> 10	Severe

2.3.2 Double oedometer test (DOT)

This test involves testing two soil specimens: one in a dry state and the other soaked in water. The potential for collapse is determined by comparing the results obtained from applying the required stress to both specimens. The soil was prepared in an oedometer mold with a specified relative density of 70% and tested until reaching a stress of 800 kPa for both the natural and soaked samples. Settlement is recorded at the stress level of 800 kPa, after which the test continues with additional loading and unloading, following a conventional consolidation test [34].

2.4 Consolidated Undrained Triaxial Compression Test

Various tests are conducted to examine the behavior of gypseous soils, including a static triaxial test (CU-test) in accordance with ASTM D4767 [35]. The static triaxial test, specifically the consolidated undrained (CU) test, is utilized to determine the total and effective shear strength properties (c' , ϕ' , c , and ϕ) of gypseous soil at a specified relative density of 70%. The standard specimens used in the test have a diameter of 38.0 mm and a height of 76.0 mm. These specimens are evaluated under different conditions, including natural water content (6%), unsaturated soil (30%, 60%, and 80%), and fully saturated soil (100%). Each specimen undergoes testing at three cell pressures of 50 kPa, 100 kPa, and 200 kPa.

For specimens with natural water content and unsaturated conditions, the gypseous soil is gradually inserted into the rubber membrane, allowing for controlled filling. Additionally, the fully saturated ($S_r = 100\%$) soil specimen is immersed in water for approximately 24 hours. Filter sheets and porous stones, measuring 38 mm in diameter and 5 mm in thickness, are placed on opposite sides of the specimen. To prevent water from entering the specimen, the membrane is securely fastened using two conventional O-rings.

3. Results and Discussion

The study aimed to investigate the behavior of unsaturated gypseous soil under different degrees of saturation. Various experiments were conducted using different levels of saturation to comprehensively analyze the response of the soil in an unsaturated state.

3.1 Physical and Chemical Properties

From Figure 1 and Table 1, it can be observed that in dry sieving, 80.0% of particles were retained on number 200 (US sieve) (consisting of 1.0% gravel and 79.0% sand), while 20.0% of particles passed through sieve number 200. Based on the results of classification tests and the Unified Soil Classification System (USCS), the gypseous soil can be classified as SM.

Gypsum, known as a binding component between soil particles, enhances their strength by altering the hydration route of calcium silicate, which typically occurs during the early stages of hydration. The presence of gypsum in the soil leads to the release of sulfate ions, which interact with the alumina phase of the soil.

Al-Mufti [5] described gypsum as a soluble salt with a molecular weight of approximately 2.20-2.60 gm/liter and a chemical formula of calcium hydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). The results indicate that gypsum (χ) is the predominant element in the gypseous soil, accounting for approximately 44.7-45.3%. Similar findings were reported by Al-Gharbawi [36] and Zidan and Hussein [37]. In natural or slightly unsaturated soil, the high calcium carbonate content (the primary form of carbonate in gypseous soil) suggests a lower clay mineral content and higher shear strength.

Due to the high concentrations of total sulfate and chloride in the soil, interactions may occur between the soil and reinforced concrete foundations, particularly when water enters the soil. The pH value of the gypseous soil is 7.23, within the normal range for soil. The soil contains a minimal amount of organic matter (0.72%) as evident from its pale color and lack of odor. The elevated total soluble salts content can cause the water table to rise during watering or the winter season.

3.2 Mineralogical Analysis

The results for the natural water content are presented in Figures 3 (a-f), displaying the findings from SEM (Scanning Electron Microscopy) analyses at the natural gypseous soil for different magnifications such as (90 x, 229 x, 300 x, 400 x, 1006, and 1200 x), respectively. Also, Figure 4 showing the findings from EDS (Electronic Dissipation X-ray scanning) analyses for the natural gypseous soil.

Based on the analysis of metallic elements in Figure 4, it was determined that the soil primarily consists of oxygen, silicon, calcium, carbon, aluminum, tantalum, and magnesium. The approximate composition of these elements is as follows: oxygen (44.21%), silicon (23.83%), calcium (15.22%), carbon (6.98%), aluminum (5.03%), tantalum (2.45%), and magnesium (2.27%). Thus, approximately 83% of the soil composition is attributed to oxygen, silicon, and carbon, while the remaining 17% is accounted for by other minerals.

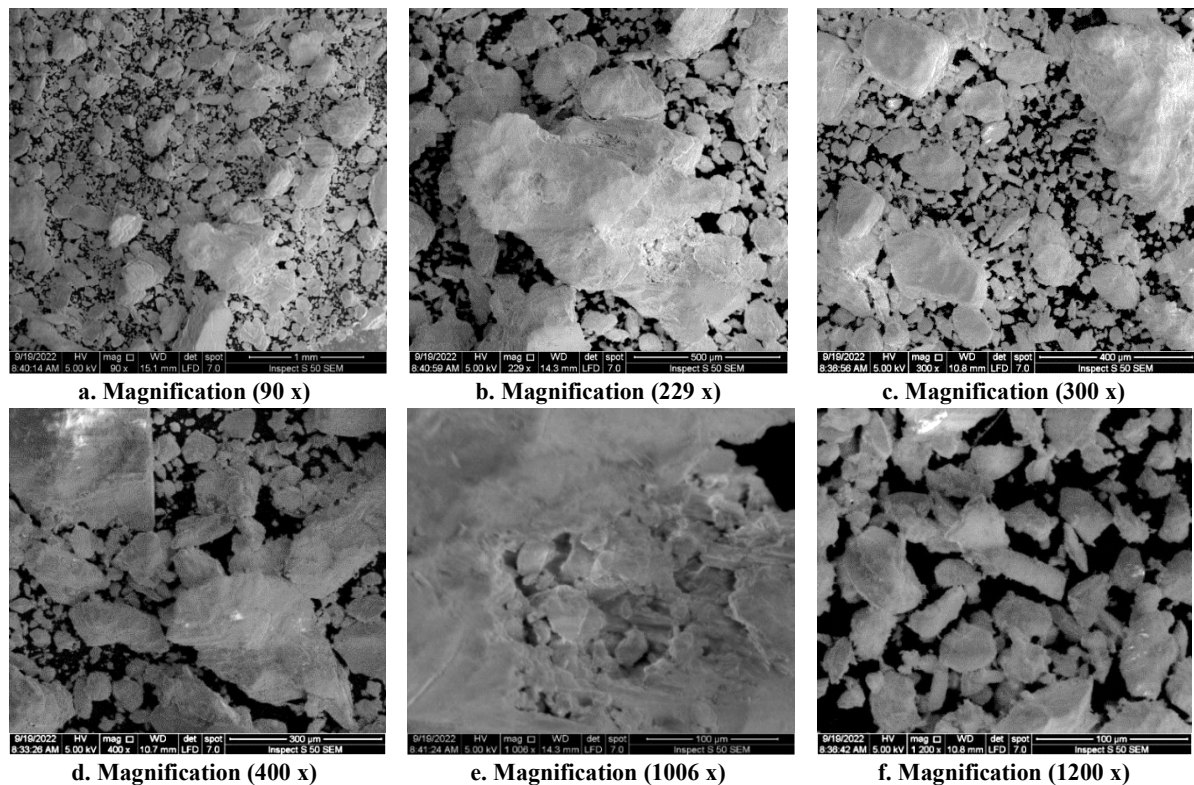


Figure 3: SEM results of the gypseous soil for different magnifications, include (a) 90 x (b) 229 x (c) 300 x (d) 400 x (e) 1006 x and (f) 1200 x

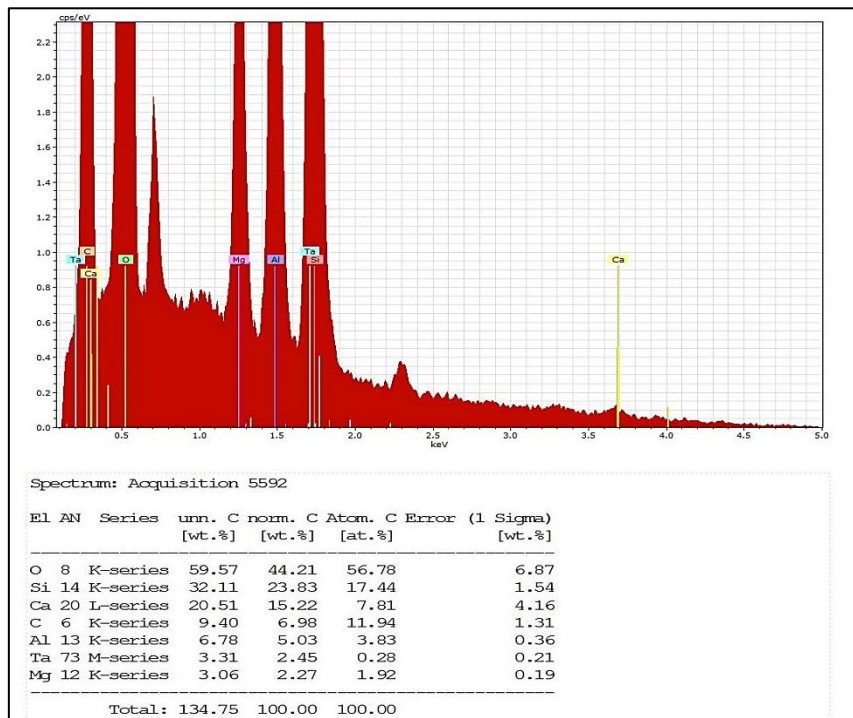
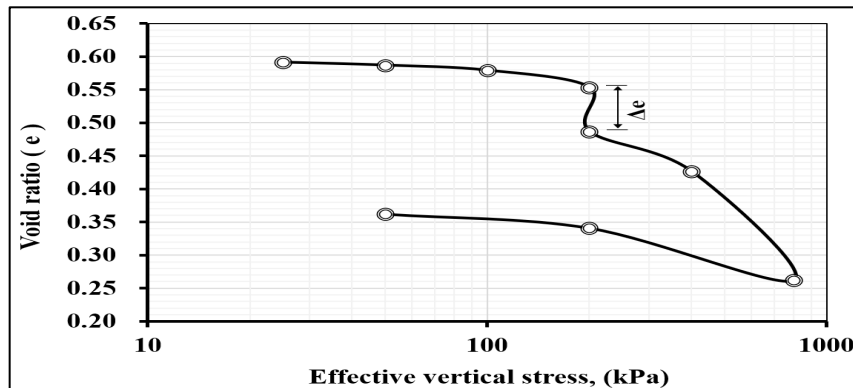


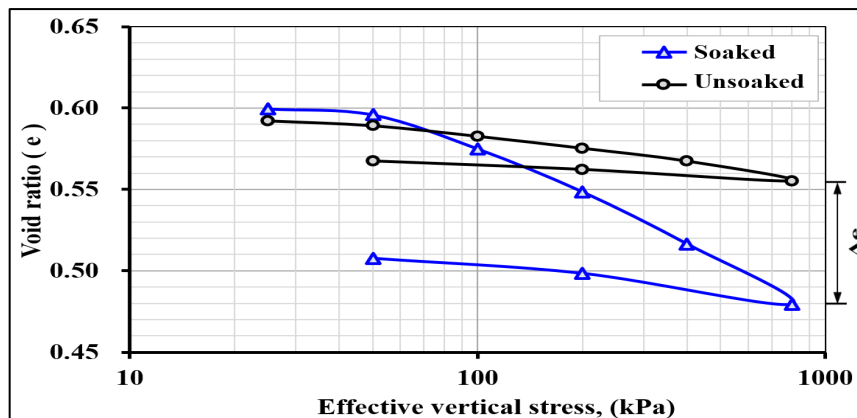
Figure 4: EDS results of the gypseous soil

3.3 Collapse Tests

The results for single and double oedometer testing at a relative density of 70% are presented in Figure 5 (a and b), respectively. Table 4 illustrates the collapse potential (C_p) and collapse index (I_c) with classification of degree of specimen collapse was determined according to ASTM D5333 [33].



a. Single oedometer test (SOT)



b. Double oedometer test (DOT)

Figure 5: Oedometer tests curves at relative density (70%), include (a) single oedometer and (b) double oedometer

Table 4: Results of oedometer test for the gypseous soil

$\rho_d, \text{gm/cm}^3$	Initial void ratio, (e_0)	Collapse strain, (Δe)	Type of collapse	Collapse index (I_c), %	Degree of collapse	Ref.
1.517	0.602	0.067	Single	4.17	Moderate	[29]
		0.076	Double	4.73	Moderate	[30]

A summary of the collapse potential (C_p) obtained from both the single oedometer test and the double oedometer test at a relative density of 70% is presented in Figure 5 and Table 4, as follows:

- The test results demonstrated an increase in the collapse potential (C_p) for both the single oedometer test and the double oedometer test as the degree of saturation decreased.
- The recorded strain for samples prepared at 70% relative density was found to be low. This behavior can be attributed to the increased soil density and volume, which enhances the bonding between the soil particles, facilitated by the presence of gypsum acting as a binder.
- At a relative density of 70%, the collapse potential obtained from the single oedometer test closely approximated the value obtained from the double oedometer test, with an average collapse potential of approximately 4%.
- Based on ASTM D5333 [33], the collapse potential of Tikrit gypseous soil at 70% relative density is classified as "Moderate" under different soaking conditions.
- A higher initial water content at a saturation degree lower than 60% reduces the collapse potential (C_p) for all soil specimens used. Decreasing the initial water content does not significantly affect the cementing effect due to the presence of gypsum between the soil particles. However, as the initial water content increases (at a saturation degree higher than 60%), the weld points weaken with the increasing water content within the soil structure.

According to Gan and Fredlund [38], collapsible soils experience significant volume changes before reaching a fully saturated state. The catalytic mechanism of collapse is associated with the strength loss resulting from the decrease in matric suction during the hydration process, which signifies the transition of the soil from an unsaturated to a saturated state.

The collapse potential for all soil types increases as the water content increases due to a reduction in matric suction. The small value of collapse obtained for all models can be attributed to various factors, including the dense condition, high compaction, capillary tension, and the presence of cementing agents between soil particles. These factors collectively contribute to the strength and rigidity of the soil, minimizing the likelihood of collapse.

3.4 Static Triaxial Test (CU-test)

Table 5 presents the results of the consolidated undrained triaxial compression test conducted on unsaturated gypseous soil. Figure 6(a) illustrate the impact of changing saturation degrees on the soil behavior while varying the effective and total cohesion of the shear strength parameters (c' and c). As well as, Figure 6(b) illustrate the impact of changing saturation degrees on the soil behavior while varying effective and total internal friction angle of the shear strength parameters (ϕ' and ϕ). Additionally, Figures (7 to 11) depict the relationship between strain and stress at different cell pressures for varying saturation degrees. Mohr's circles are utilized to calculate the shear strength parameters, including effective and total stresses. Furthermore, the figures display Mohr's circles representing shear strength parameters for both total and effective stresses at different degrees of saturation for a relative density of 70%. Where Figures (7, a-c; 8, a-c; 9, a-c; 10, a-c, 11, a-c) shown the relationships between stress and stain at cell pressures 50, 100, and 200 kPa per saturation degree, respectively. While Figures (7d; 8d; 9d; 10d; 11d) shown the relationships shear strength characteristics for effective and total stresses at various saturation degrees.

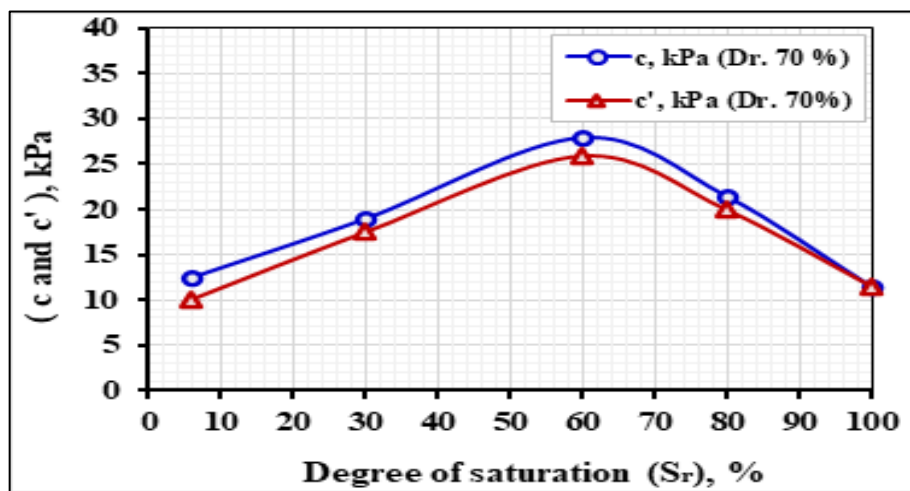
The parameters of internal friction angle (ϕ) and cohesion (c) are present in both unsaturated and saturated samples, although with varying magnitudes. The cohesion parameter increases with the increasing saturation degree of the soil until reaching 60%, after which it decreases until the soil becomes fully saturated (100%). Additionally, as the moisture content of the gypseous soil increases, the internal friction angle parameter decreases for all samples. This can be attributed to the partial dissolution of the gypsum element upon reacting with water. The solubility of gypsum increases when the soil is subjected to horizontal and vertical loads over time, leading to the soil's eventual collapse under extreme conditions.

The gypsum element is a lightweight substance with a specific gravity of 2.30 compared to conventional soils, and it acts as a stable expanding component within the soil. As a result, gypsum has an inverse relationship with the density of dry soil, causing a decrease in soil density [39]. This is due to the presence of two water molecules within the gypsum element, allowing the soil to absorb minimal moisture without affecting its chemical composition. However, with the introduction of more water, the solid state of gypsum transitions into a solution, thus affecting its chemical makeup [40]. Furthermore, Aldaood et al. [41] discovered that the presence of soluble gypsum elements in soil samples induces osmotic suction, resulting in additional water absorption.

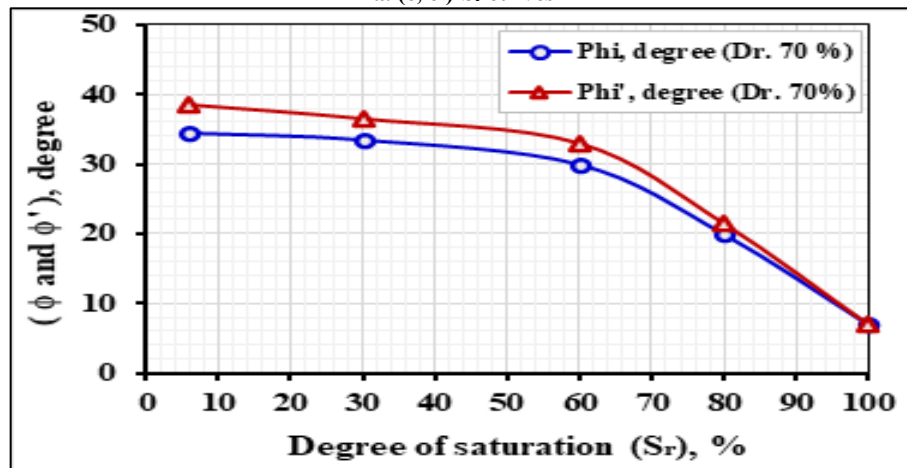
According to Fattah et al. [42], an increase in gypsum concentration leads to a reduction in the shear strength parameters (ϕ and c). The presence of gypsum in soil, especially when not exposed to water, has minimal impact on its behavior compared to soils without gypsum or when subjected to applied stresses. However, when pure water infiltrates the gypseous soil at high rates, it causes the chemical bond between gypsum and the soil particles to weaken. This leads to the decomposition of gypsum components, resulting in a decrease in the shear resistance of unsaturated gypseous soil. Consequently, the soil may fail under low stresses, leading to increased vertical settlement or exceeding the permissible limits of longitudinal strain.

Table 5: A summary of results for consolidated undrained triaxial compression test for the gypseous soil with relative density 70% at varying saturation degrees

No.	S _r , %	φ, degree	c, kPa	φ', degree	c', kPa	σ ₃ , kPa	σ _d , kPa	σ ₁ , kPa	u _d , kPa	ε _l , %
1	6% (Natural)	34.5	12.5	38.5	10	50	171.8	221.8	10.8	1.0
						100	300.8	400.8	24.4	1.5
						200	557.5	757.5	49.4	2.5
2	30%	33.5	19	36.5	17.5	50	195.4	245.4	8.2	1.8
						100	317.9	417.9	19.0	3.4
						200	576.6	776.6	33.1	9.0
3	60%	30	28	33	26	50	199.5	249.5	7.1	6.0
						100	304.5	404.5	13.9	8.4
						200	507.3	707.3	30.8	17.5
4	80%	20	21.5	21.5	20	50	117.9	167.9	1.8	7.0
						100	165.9	265.9	7.1	10.0
						200	271.1	471.1	16.5	17.5
5	100%	7	11.5	7	11.5	50	39.7	89.7	1.2	3.4
						100	53.3	153.3	1.6	3.6
						200	80.2	280.2	1.8	3.8



a. (c, c')-S_r curves



b. (φ, φ')-S_r curves

Figure 6: Shear strength parameters with different degrees of saturation of the gypseous soil at Dr. 70%, include (a) cohesions parameters with saturation degrees and (b) internal friction angles parameters with saturation degrees

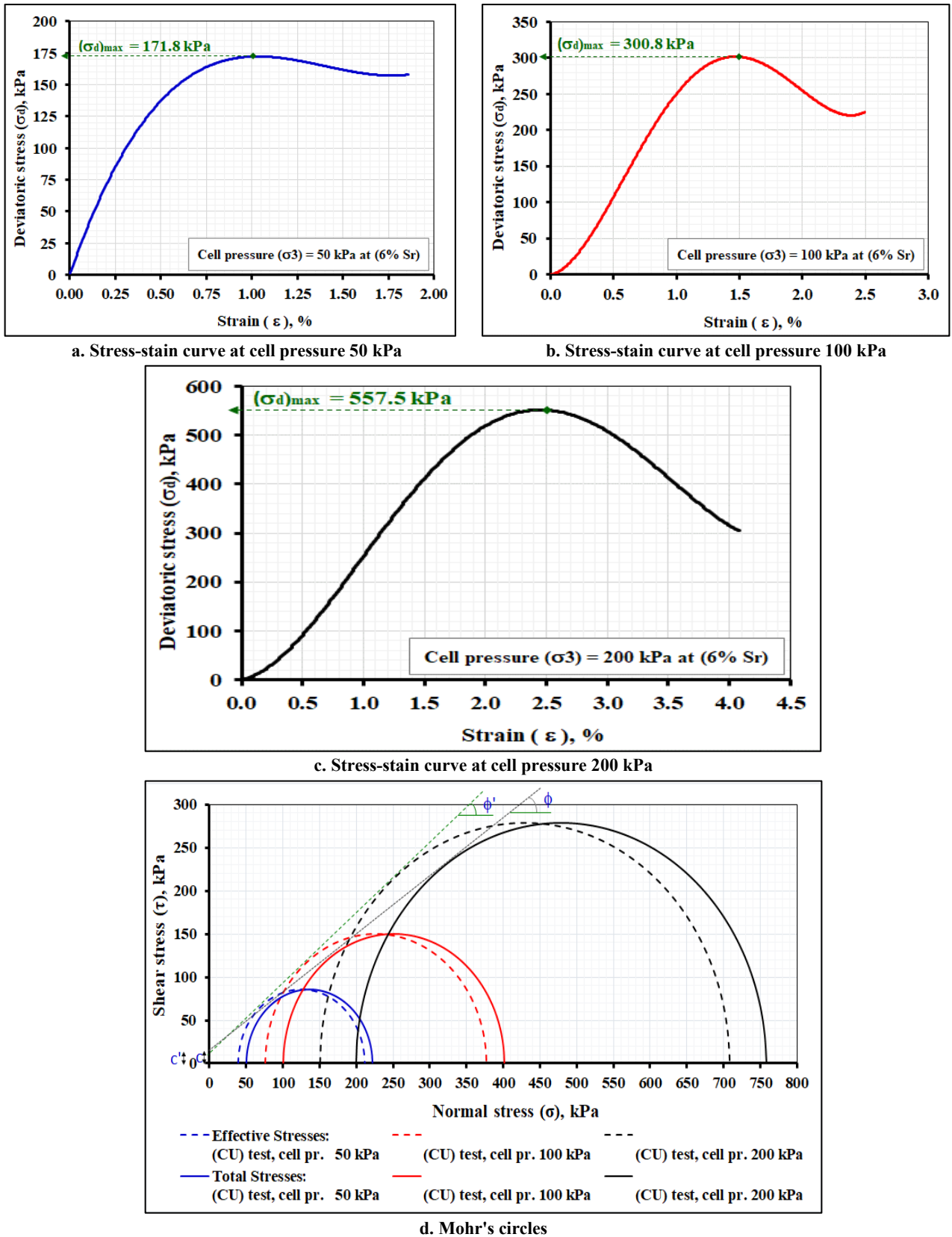


Figure 7: Curves of (stress - strain) with shear strength characteristics of the natural gypseous soil at saturation degree 6%, and relative density 70%, include (a) stress-strain curve at 50 kPa of σ_3 (b) stress-strain curve at 100 kPa of σ_3 (c) stress-strain curve at 200 kPa of σ_3 and (d) Mohr's circles

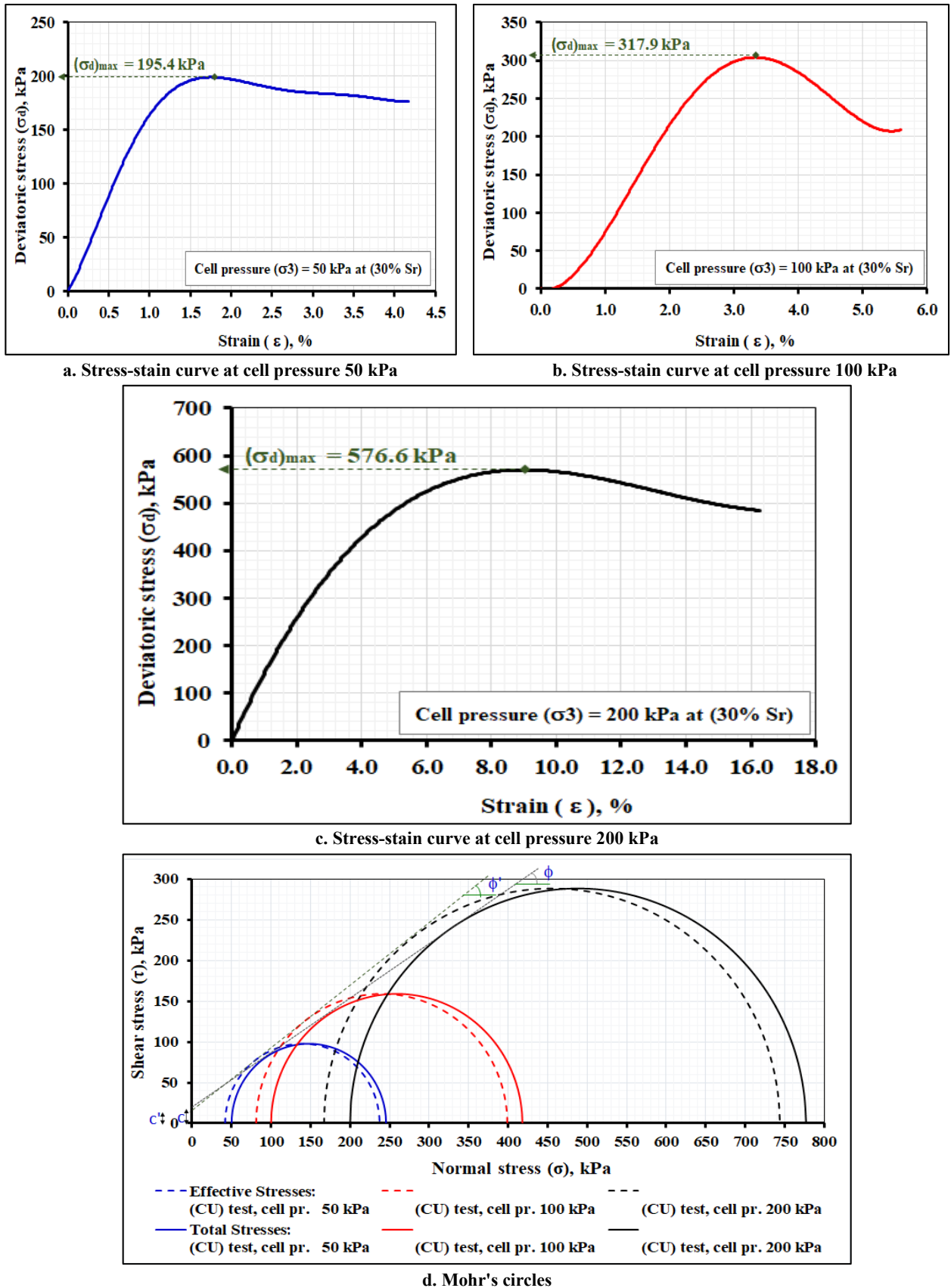
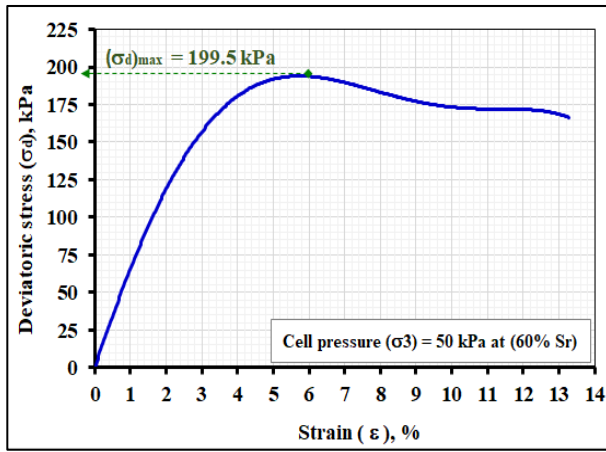
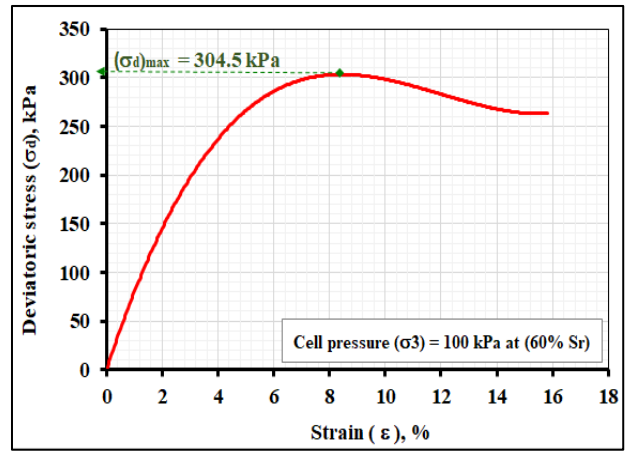


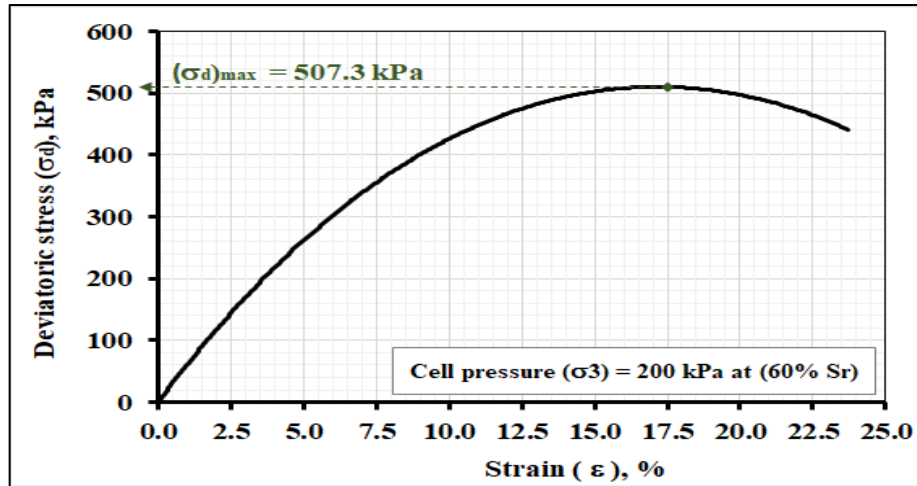
Figure 8: Curves of (stress - strain) with shear strength characteristics of the unsaturated gypseous soil at saturation degree 30%, and relative density 70%, include (a) stress-strain curve at 50 kPa of σ_3 (b) stress-strain curve at 100 kPa of σ_3 (c) stress-strain curve at 200 kPa of σ_3 and (d) Mohr's circles



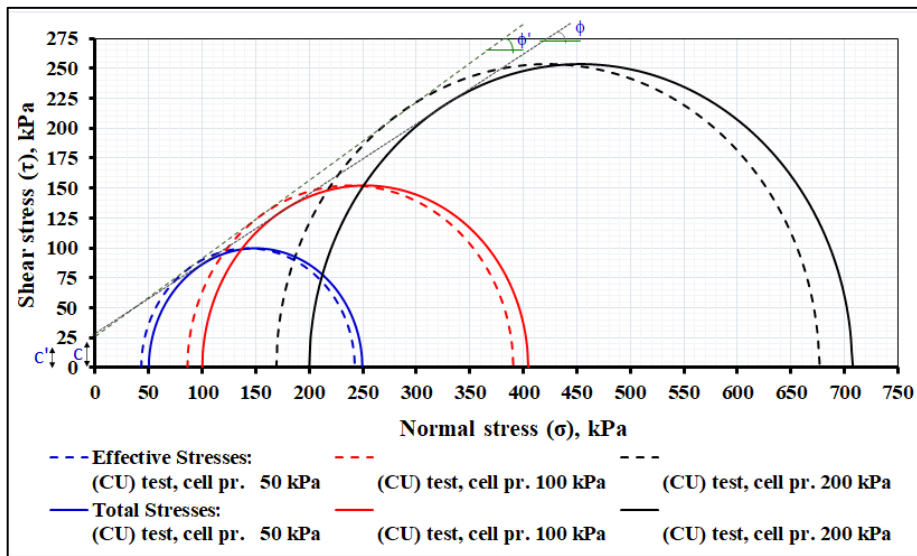
a. Stress-strain curve at cell pressure 50 kPa



b. Stress-strain curve at cell pressure 100 kPa

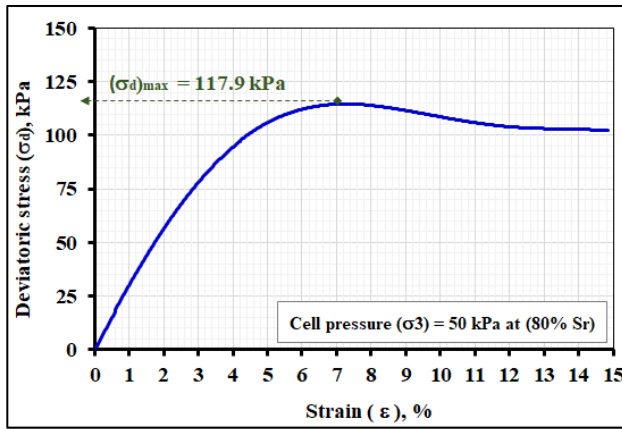


c. Stress-strain curve at cell pressure 200 kPa

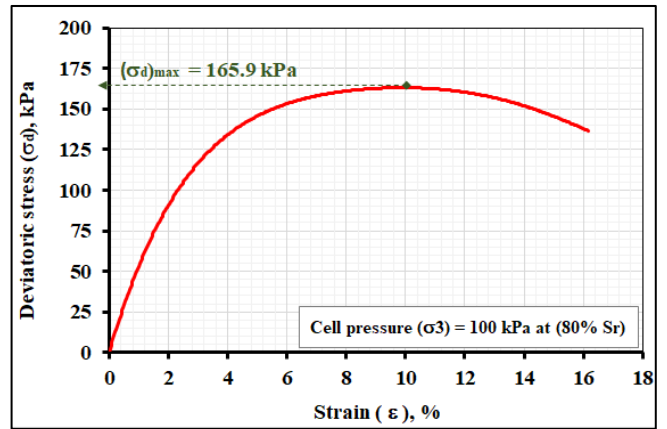


d. Mohr's circles

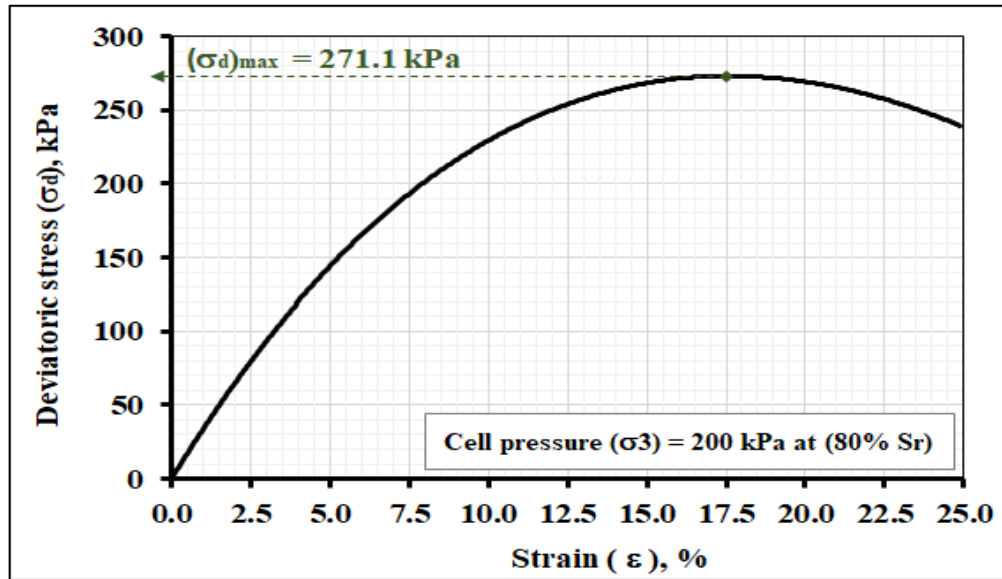
Figure 9: Curves of (stress - strain) with shear strength characteristics of the unsaturated gypseous soil at saturation degree 60%, and relative density 70%, include (a) stress-strain curve at 50 kPa of σ_3 (b) stress-strain curve at 100 kPa of σ_3 (c) stress-strain curve at 200 kPa of σ_3 and (d) Mohr's circles



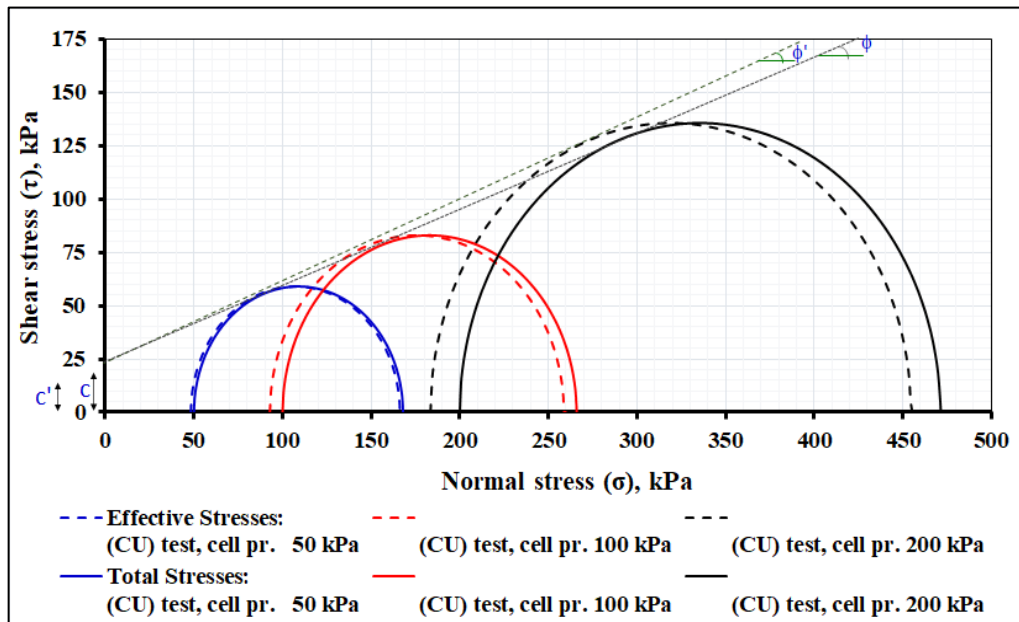
a. Stress-strain curve at cell pressure 50 kPa



b. Stress-strain curve at cell pressure 100 kPa

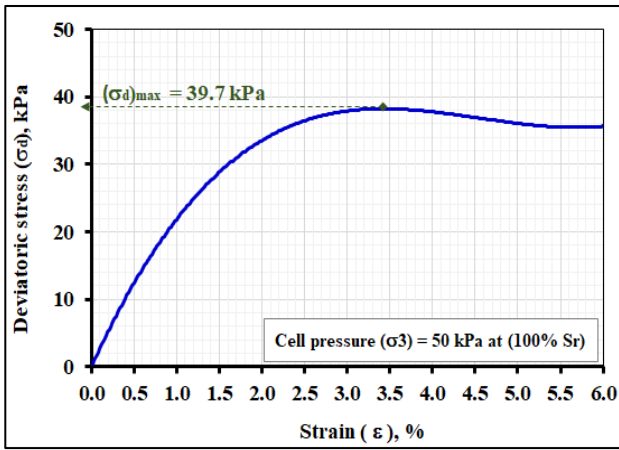


c. Stress-strain curve at cell pressure 200 kPa

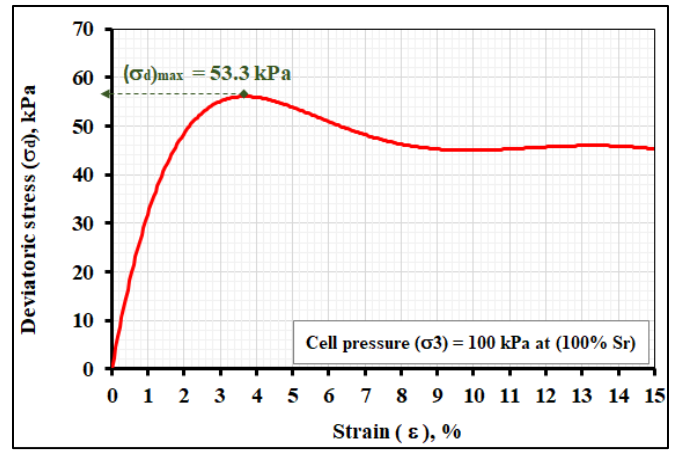


d. Mohr's circles

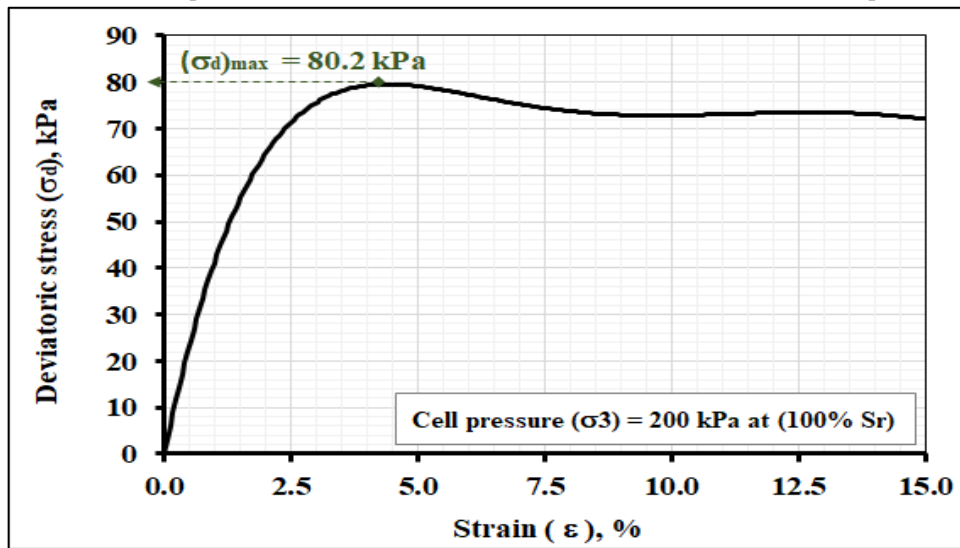
Figure 10: Curves of (stress - strain) with shear strength characteristics of the unsaturated gypseous soil at saturation degree 80%, and relative density 70%, include (a) stress-strain curve at 50 kPa of σ_3 (b) stress-strain curve at 100 kPa of σ_3 (c) stress-strain curve at 200 kPa of σ_3 and (d) Mohr's circles



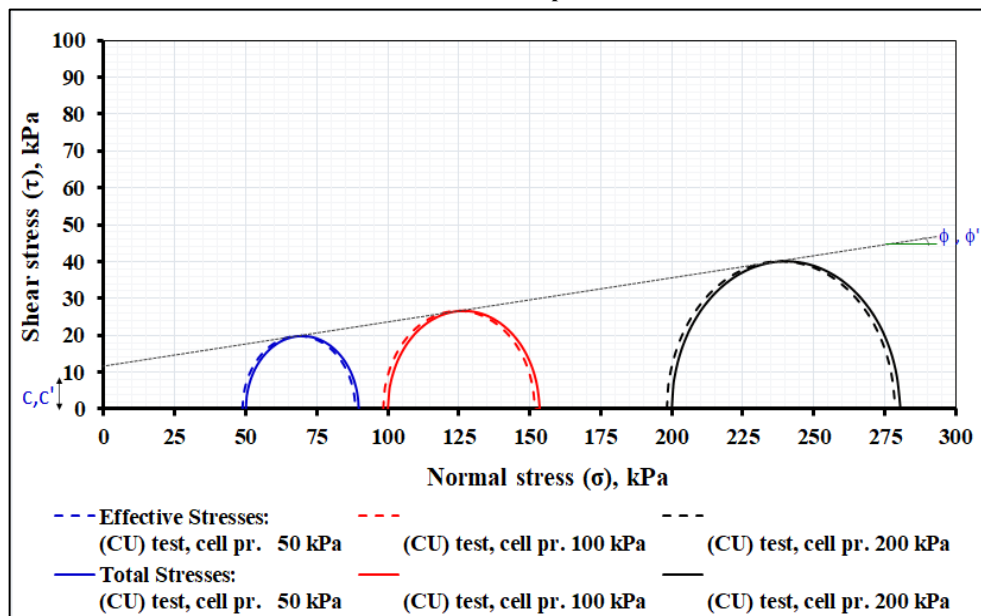
a. Stress-strain curve at cell pressure 50 kPa



b. Stress-strain curve at cell pressure 100 kPa



c. Stress-strain curve at cell pressure 200 kPa



d. Mohr's circles

Figure 11: Curves of (stress - strain) with shear strength characteristics of the gypseous soil at fully saturation degree 100%, and relative density 70%, include (a) stress-strain curve at 50 kPa of σ_3 (b) stress-strain curve at 100 kPa of σ_3 (c) stress-strain curve at 200 kPa of σ_3 and (d) Mohr's circles

It was discovered that increasing the wetness of the gypseous soil at all degrees of saturation induces a reduction in the angle of internal friction at the two types of effective and total stresses (ϕ' and ϕ). The reduction value varied from ($38.5^\circ-7^\circ$) in terms of effective stresses, and between ($34.5^\circ-7^\circ$) in terms of total stresses. Whereas, it was discovered that the strength of soil cohesion as well as effective and total stresses (c' and c) raised with increasing gypseous soil moisture up to 60% saturation, this results in a rise in soil shear strength. The effective stress rise varied from (10-26 kPa), and the total stress rise ranged from (12.5-28 kPa). The strength thereafter steadily decreased at the saturation limit (80 and 100%, respectively). As a result, the shear strength of the soil decreases, with the magnitude of the drop ranging from (20-11.5 kPa) in terms of effective stresses, and from (21.5-11.5 kPa) in terms of total stresses. Furthermore, very close values for both the effective and total shear strength parameters in the soil were measured while the soil became fully saturated 100%, as verified by Lu and Likos [43].

Different types of gypsum soil can be utilized to a certain extent in cases of short-term flooding. However, in the context of long-term floods, settling increases due to the dissolution of salts and gypsum. Proper compaction is crucial for establishing a stable foundation for these soils. The primary factors influencing the settling ratio include the predominant gypsum content, the extent of salt leaching, the mineralogy of the soil, the soil characteristics, and the applied load.

4. Conclusion

The following conclusions can be drawn from this study based on the research results:

- a) The strain observed in soil prepared at 70% relative density is low. This behavior can be attributed to the increased soil density and volume, which enhances the bonding between the soil particles, facilitated by the presence of gypsum acting as a binder. At a relative density of 70%, the collapse potential obtained from the single oedometer test closely approximated the value obtained from the double oedometer test, with an average collapse potential of approximately 4%. The collapse rate of Tikrit gypseous soil with a relative density of 70% can be classified as "Moderate" under various soaking pressures.
- b) A high initial water content at a saturation degree below 60% reduces the potential for collapse (C_p) in all soil specimens used. Decreasing the initial water content does not significantly affect the bonding points caused by the cementing effect of gypsum between the soil particles. However, as the initial water content increases (at a saturation degree above 60%), the bonding points weaken due to the increased water content within the soil structures.
- c) Internal friction angles (ϕ , ϕ') and cohesion (c , c') are present in both unsaturated and saturated specimens, although at varying rates. Cohesion increases with increasing soil saturation up to 60%, after which it decreases until reaching full saturation (100%). Moreover, as the moisture content of the gypseous soil increases, the internal friction angles gradually decrease for the samples.
- d) Increasing the moisture content of the gypseous soil at different degrees of saturation leads to a reduction in the internal friction angles under both effective and total stresses. The reduction ranges between 38.5° and 7° for effective stresses, and between 34.5° and 7° for total stresses. The cohesion of the soil under both effective and total stresses increases as the moisture content of the gypseous soil rises up to 60% saturation, resulting in an increase in soil shear strength.
- e) When the gypseous soil reaches full saturation (100% degree of saturation), very close values are obtained for both effective and total shear strength parameters.

Acknowledgment

The authors would like to acknowledge the Civil Engineering Department of the University of Technology – Iraq for support.

Author contributions

Conceptualization, A. Abood, M. Fattah and A. Al-Adili; methodology, A. Abood; software, A. Abood; validation, A. Abood, M. Fattah and A. Al-Adili; formal analysis, A. Abood, M. Fattah and A. Al-Adili; investigation, A. Abood, M. Fattah and A. Al-Adili; resources, A. Abood; data curation, A. Abood; writing—original draft preparation, A. Abood, M. Fattah and A. Al-Adili; writing—review and editing, A. Abood, M. Fattah and A. Al-Adili; visualization, M. Fattah and A. Al-Adili; supervision, M. Fattah and A. Al-Adili; project administration, M. Fattah and A. Al-Adili. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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