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Research article

EFFECT OF WETTING PROCESS WITH PRESENCE OF MATRIC SUCTION ON UNSATURATED GYPSEOUS SAND SOILS

有吸力的润湿过程对不饱和糖浆土的影响

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Abstract
This paper presents the results of laboratory experiments on the effect of matric suction on the compressibility of unsaturated gypsum sand soil under various types of loading. The soil samples were obtained from Al-Najaf city in Iraq with gypsum contents of 14 %, 22 % and 29 %. A wetting-process tests were conducted in a modified triaxial cell on these soil. This procedure likes when a structure has been constructed and the degree of saturation of a foundation soil is increased (decreasing in matric suction). Four matric suctions were adopted; 100, 60, 30 and zero percentages of initial matric suction under two different mean net stresses; 100 kPa and 200 kPa. The changes in the degree of saturation may be due to rainfall, water table rising and/or leaking of sewage and water pipes. The results from this path revealed that the volumetric strains are increased with decreasing of the matric suction and increasing of the gypsum content.

Keywords: Al-Najaf, Gypsum Sand Soil, Modified Triaxial Cell, Volumetric Strains, Matric Suction.

摘要 本文介绍了在不同载荷下基质吸力对非饱和石膏砂土可压缩性影响的实验室实验结果。 从伊拉克的纳杰夫市获得的土壤样品中的石膏含量分别为 14 %，22 % 和 29 %。 在这些土壤上的改良三轴孔中进行了润湿过程测试。 此过程就像在构造结构并增加基础土壤的饱和度（降低基质吸力）时一样。 采用四次基质抽吸； 在两种不同的平均净应力下，初始矩阵吸力的百分比分别为 100、60、30 和 零； 100 千帕和 200 千帕。 饱和度的变化可能是由于降雨，地下水位上升和/或污水和水管泄漏造成的。 该路径的结果表明，体积应变随着基质吸力的减少和石膏含量的增加而增加。

关键词: 纳杰夫，石膏砂土，改良的三轴细胞，体积应变，基质抽吸。

I. INTRODUCTION

Gypsum rich soils cover a wide area of the Middle East; they cover large areas of Iraq. Al-Najaf city is constituted one of the gypsiferous rich soils cities in Iraq. These kind of soils face sudden collapse during water presence, many structures have been observed in different places of Iraq, it has been stated that several structures that have been constructed on these soils have cracks in different patterns and unleveled settlements when they were exposed to water [1].

Calcium sulphate dihydrate (gypsum) or as $CaSO_4.2H_2O$ behaves stable due to the two bonds of water [2]. Sudden collapse can be occurred in gypsiferous soils upon wetting [3]. In case of rising of water table, from different reasons, the softening of gypsum materials that are between the soils particles will be occurred. In this state, the bonds that the gypsum materials made them between the soil particles are broken [4]. Damaging and cracks of the structures are possible issues when water attacks the supporting gypseous soils [5], [26].

Several researchers investigated the effect of gypsum content on the different soil properties after water soaking with different time durations. Razouki and Al-Azawi depended on CBR tests and they stated that the soaking duration has a valuable effect on the deformation of soils with gypsum content and this deformation is increased with increasing the soaking duration [6]. Salman tested soil samples from Baghdad city after soaking of 12 samples and he specified a clear reduction in cohesion and marginal reduction in angle of internal friction [1]. Mahmood stated that there are a decreasing in the soil shear strength parameters after been subjected to the pre-long duration of soaking in Al-Najaf city [7]. Mahmood determined an increase in the maximum laboratory dry density after different soaking durations for different soils samples from Al-Najaf city [8]. Mahmood et al. investigated the effect of different soaking periods up to two weeks on low gypseous sand soils (< 5 %) from Al-Najaf city using Oedometer test and they concluded that there were noticeable increase in the settlement but no collapse potential in the soil samples according to Jennings and Knight [9]. Pore water pressure is increased due to rainwater infiltration that is the most dominant failure mechanism of Mechanically Stabilized Earth (MSE) wall due to the backfill of embankment [10].

Gypsiferous soils have been studied within the conventional soil mechanics (saturated condition). Gypsiferous soils are found in arid and semi-arid areas (unsaturated) and soil characteristics may be largely different [5]. Water infiltration leads to decrease in soil suction, which may destabilize the buried services, such as, water pipes [11]. Soil deformation and shear strength reduction due to wetting are the main reasons of collapse [12].

Triaxial apparatus for unsaturated soil have been developed by many researchers. Aversa and Nicotera [13], Cabarkapa and Cuccovillo [14], Padilla et al. [15] and Haeri et al. [16] designed and developed the conventional triaxial device to work with matric suction (**ψ**). Estabragh and Javadi experimented the unsaturated silty soil and they concluded that the yield stress and dilatancy of the samples increases with increases the suction [17]. Haeri et al. examined the soil specimens from northeast of Iran and they indicated that higher mean net stress (Pn) caused more severe collapse during wetting [16]. Yao et al. investigated the unsaturated resilient modulus of soils and they predicted a model relating the variables including the minimum bulk stress, octahedral shear stress and matric suction and this model can be applicable for various soils. They stated that the resilient modulus increases with increasing matric suction [18]. Haeri et al. was owing complications in preparing of undisturbed samplings from collapsible soils and they stated that many researchers performed tests on remolded specimens and the sensitivity of the soils has been ignored [19].

II. Research Aim

Most of the available researches (field and laboratory) on the behavior of the gypsiferous soils in Iraq are achieved according to the saturated conventional method. This paper investigates the deformation of Al-Najaf city soil for different gypsum contents under unsaturated testing and for wetting path to clarify the effect of matric suction presence on the soil behavior.

III. Material, Tools and Methodology

A. Material Properties

As shown in figure 1, the samples were selected based on the gypsum map of Al-Najaf city as mentioned by Al-Shakerchy [20]. These samples were taken from three different sites at depth of 0.5 m in Al-Najaf city, Iraq. The soil samples are well graded sand (SW) according to Unified Soil Classification System (USCS) and they are mainly sand with more than 70 %. Table 1 summarizes the soil properties. The soil samples are named G1, G2 and G3 based on the gypsum content 14 %, 22% and 29 % respectively.

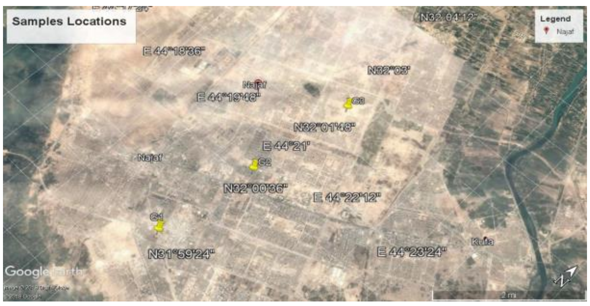

Figure 1. Locations of the samples.

Table 1.
Soil properties of the selected sites

Test name	Test specification	G1	G2	G3
Soil classification sieve analysis), USCS	ASTM C136/C136M−14	SW	SW	SW
Specific gravity, Gs	ASTM D854-14	2.5	2.43	2.38
Gypsum content, %	ASTM C25-99	14	22	29
Natural water content (wn), %	ASTM D698-00a	3	3	3
Field density (sand con test), gm/cm^3	ASTM D1556/D1556M−15ε1	1.824	18.26	1.829
Max. dry density (proctor test), gm/cm^3	ASTM D698-00a	1.84	1.83	1.825
Optimum moisture content (proctor test), %	ASTM D698-00a	14.2	14.8	15
Void ratio (e)	-	0.35	0.32	0.3

Barazanji in Iraq has developed a gypsiferous classification system [21], based on this classification, G1 sample is moderately gypsiferous, G2 is highly gypsiferous and G3 is also highly gypsiferous. According to Table 1, the specific gravity for G3 is lower than G1 and G2, and the specific gravity for G2 is also lower than G1, this behavior instructs that the gypsum materials are lighter than the same size of the soil without gypsum materials. So, the presence of gypsum materials is very effective on the soil properties (mechanical and physical properties) [22], [23].

The results of the Scanning Electron Microscopy (SEM) test for the remolded specimen in the natural moisture content indicate two different states; the first is the gypsum materials cover the soil particles by a thin layer and work as a bond between soil particles as shown in figure 2, while the second one is the gypsum materials are grouped together to make a strong link between soil particles as shown in figure 3.

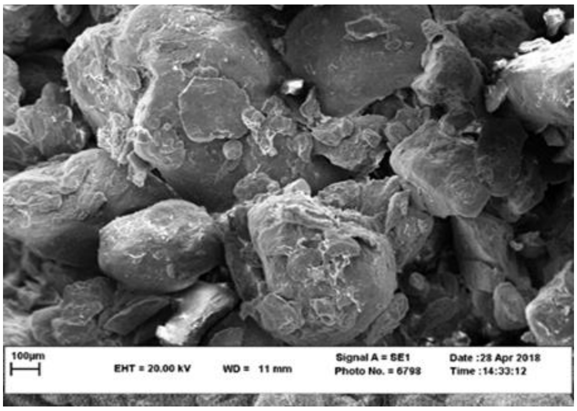

Figure 2. Gypsum materials covered soil particles for the tested specimen.

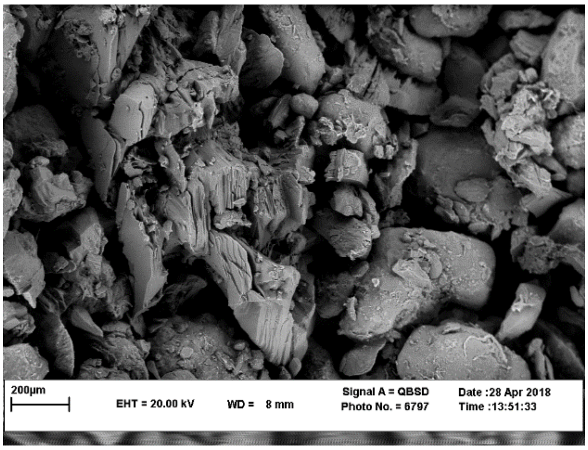

Figure 3. Grouped gypsum materials for the tested specimen.

In both states, the gypsum materials work as cemented agent in dry state, therefore, the soil has an apparent cohesion. Once this soil is wetted, this cohesion is eliminated and the flexibility in gypsum materials occurs, then, the collapse will be happened.

B. Tools and Equipments

Many devices have been designed and developed to convert the saturated (conventional) triaxial test device to the unsaturated status by applying suction control. In this paper, the unsaturated triaxial device was adjusted and calibrated in the laboratory of soil mechanic in the faculty of engineering in Ferdowsi University of Mashhad (FUM). Figure 4 illustrates the schematic diagram of the modified triaxial test device.

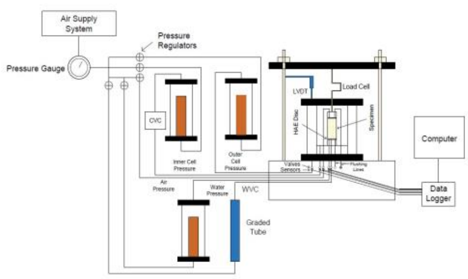

Figure 4. Schematic shape of the modified triaxial test device.

The unsaturated equipments that were defined by Fredlund and Rahardjo are clarified in figures 5-8; High Air Entry ceramic disc (HAE), top cap, air pressure control and volume change control device [24]. The 7 cm HAE (> 6.3 cm original diameter), as shown in figure 5, is placed on a grooved base plated (figure 6) and these grooves are working like a channel to flush out air bubbles that were confined before the work starting by the flush valve. The pore water pressure is applied through the HAE disc that was tied on the grooved base by screws and O-ring to prevent water leaching, while the air pressure is applied and controlled using the top cap as shown in figure 7. A 1 Bar HAE ceramic disc (100 kPa air entry value) was selected depending on the natural moisture content that matched 30 kPa matric suction from SWCCs for both samples. The size of the sample in the triaxial test is 7 cm in diameter and 14cm in height, it has an inner cell (figure 7) and outer cell (figure 8). The inner cell is used for measuring volume changes of the specimen from the amount of water that enters and exits to/from the inner cell, while the outer cell is used for preventing the radial deformation of the inner cell. Linear variable differential transformer (LVDT) with an accuracy of 0.01 mm/min is placed outside the cell to measure the axial displacement of the specimen during the test. The maximum displacement that can be measured by LVDT is about 10 cm and the vertical rod workability is 5000 N and its accuracy is 1 N. A cell volume change device (CVC) with a LVDT sensor is used to calculate the total volume change of the soil by measuring the fluctuations of water level inside the inner cell. Drained water are calculated by measuring the amount of water drained in or out of the tested specimen by a graded tube; water volume change (WVC) as shown in figure 7.

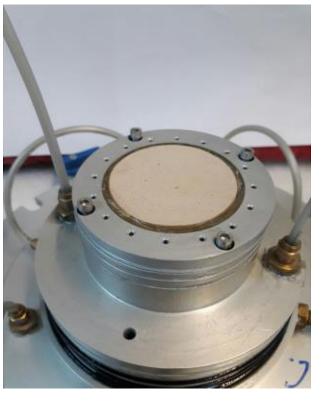

Figure 5. HAE ceramic disc (1 bar).

Figure 6. Grooved base plate.

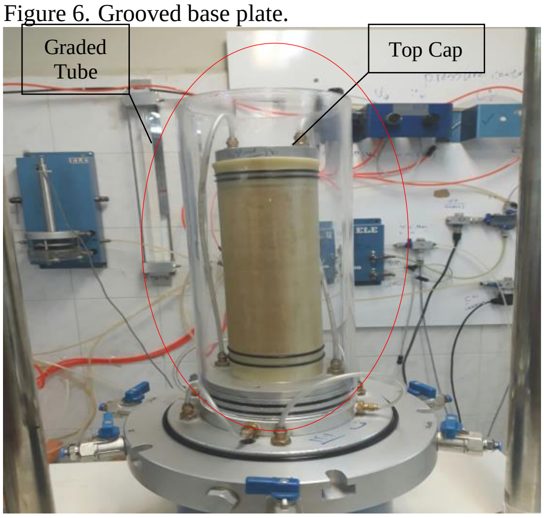

Figure 7. Inner cell.

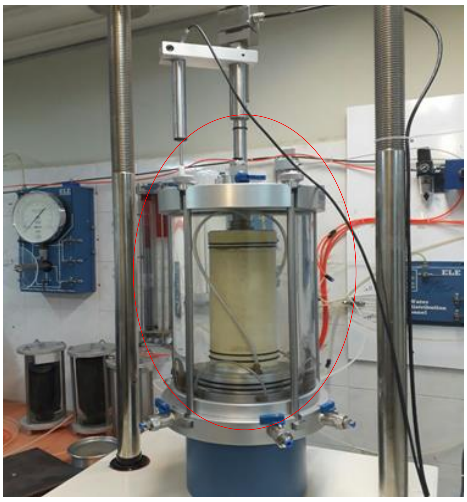

Figure 8. Outer cell.

C. Determination of Soil-Water Characteristic Curves (SWCCs)

For each sample, the SWCC was determined using filter paper method for wetting path and pressure plate test for drying path. The filter paper method was done depending on ASTM D5298-03 while the pressure plate test method was performed according to ASTM D2325-68. The laboratory test results for the three tested samples indicated that they have the same trend in both directions; wetting path and drying path except in the saturation state because it depends on the void ratio and the gypsum content that they have. The results of drying and wetting paths of the SWCC are shown in figures 9-11. The soil suction of all specimens at their initial moisture content (in site, ψo) was measured using the filter paper method technique, this method indicated an average of initial suction value of about 30 kPa for the three tested samples.

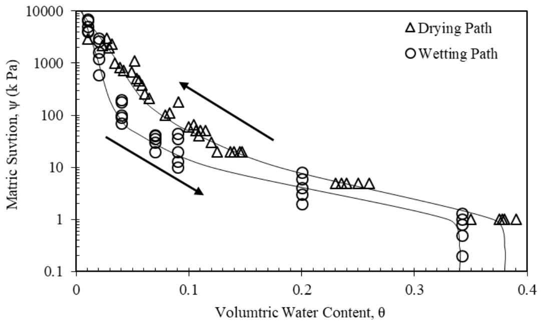

Figure 9. SWCC of G1 specimen.

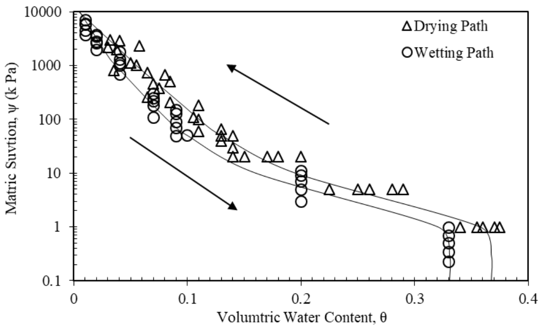

Figure 10. SWCC of G2 specimen.

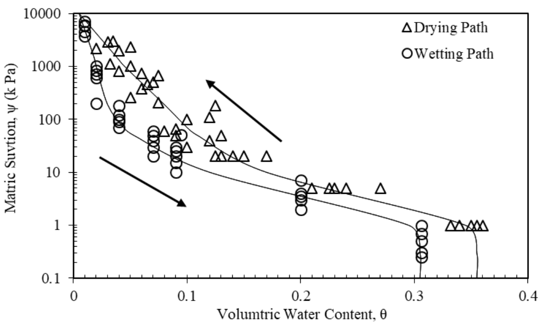

Figure 11. SWCC of G3 specimen.

D. Laboratory Tests Procedure and Specimen Preparation

In the current study, a modified triaxial device was used to investigate the behavior of gypsiferous soils under presence of different matric suctions. A wetting-path is adopted likes when a structure has been constructed and the degree of saturation of a foundation soil is increased (decreasing in matric suction). The changes in degree of saturation may be due to rainfall, water table rising and/or leaking of sewage and water pipes.

According to Ladd, the tested soil specimens were prepared in cylindrical mold in equal eight layers (weight and height) and there were two filter papers and two porous ceramic filters up and down the specimen to prevent any blinding for the HAE ceramic disc [25]. The dry densities of the tested specimens (G1, G2 and G3) were 90 % of the maximum dry density of standard Proctor test as shown in Table 1. The triaxial tests program is scheduled in Table 2.

Table 2.
Wetting-path tests program

Soil type	Test No.	σ3, kPa	Pn, kPa	Stage	(ψ), kpa
G1	1	50	100	1	ψinitial
				2	0.6 ψinitial
				3	0.3 ψinitial
				4	Zero
	2	100	200	1	ψinitial
				2	0.6 ψinitial
				3	0.3 ψinitial
				4	Zero
G2	1	50	100	1	ψinitial
				2	0.6 ψinitial
				3	0.3 ψinitial
				4	Zero
	2	100	200	1	ψinitial
				2	0.6 ψinitial
				3	0.3 ψinitial
				4	Zero
G3	1	50	100	1	ψinitial
				2	0.6 ψinitial
				3	0.3 ψinitial
				4	Zero
	2	100	200	1	ψinitial
				2	0.6 ψinitial
				3	0.3 ψinitial
				4	Zero

In wetting-path methodology, for the same gypsum contents; G1, G2 and G3, the specimens were examined to clarify the effect of decreasing in matric suction under a specific load. Six tests were performed in unsaturated state conditions; two tests for each gypsum content under two mean net stresses (Pn) of 100 kPa and 200 kPa. Every tested specimen was started with an initial confining stress (σ_3 = 10 kPa) to avoid any shape deformation and/or collapse due to specimen weight. Furthermore, these tests were started with the initial matric suction (ψo = 30 kPa) which was determined based on filter paper test method. The calculation of initial matric suction depended on the natural moisture content in the site (3 % for all samples G1, G2 and G3). A 1 bar (100 kPa) ceramic disc was used in these tests corresponding to the initial matric suction. Four matric suction levels were adopted to cover all three areas in Soil Water Characteristic Curves (SWCCs drying-path and wetting-path for G1, G2 and G3). These matric suctions were initial matric suction (ψo), 60 % ψo, 30 % ψo and zero matric suction (saturated state with HAE disc). To satisfy these matric suction levels, the air pressure (Ua) was set and applied at the top of the specimen (throughout the cap) and the water pressure (Uw) was set and applied at the bottom of the specimen (from the graded tube throughout the grooved base plate). The specimen was left for 72 hours to reach to the equilibrium state with no entry of water from the graded tube to the specimen.

The load (Pn) of 100 or 200 kPa was applied and left for three days to make certain the initial matric suction kept its value that had it before. Then, the wetting-path was started with the three stages of matric suctions (60 % ψo, 30 % ψo and zero matric suction). During each matric suction stage, the cell volume changes (CVC) in the inner cell and outer cell were recorded to calculate the volumetric strains **(εv)** after neglecting the deformation of the outer cell wall and sinking of the load rod.

IV. Results

The results included two parts; matric suction equilibrium stage in the beginning of each test, and the second part is wetting-path. In this research, for each test, the initial matric suction that was determined based on initial moisture in the site was applied as mentioned before. The matric suction is defined as the difference between the air pressure and water pressure.

To achieve the selected matric suction (initial), i.e., the water volumes changes (WVCs) that entered to the specimen were recorded and set as positive values as shown in figures 12-14. These records were used to calculate the degree of saturation to confirm that the pointed volumetric water content (θ) has been achieved. For all different soil samples with different gypsum contents (G1, G2 and G3), the required time to reach to the equilibrium stage conditions was 48 hours in zero matric suction, this was fixed in all unsaturated tests to assess the specimens in the same conditions.

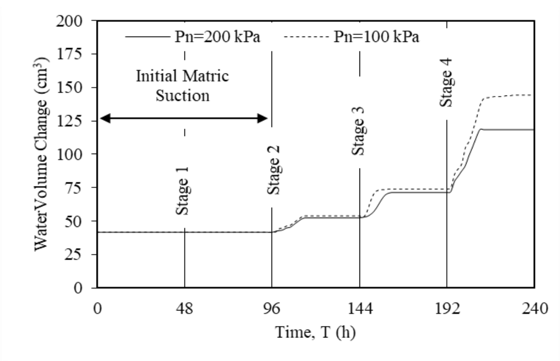

Figure 12. WVCs of G1 specimen.

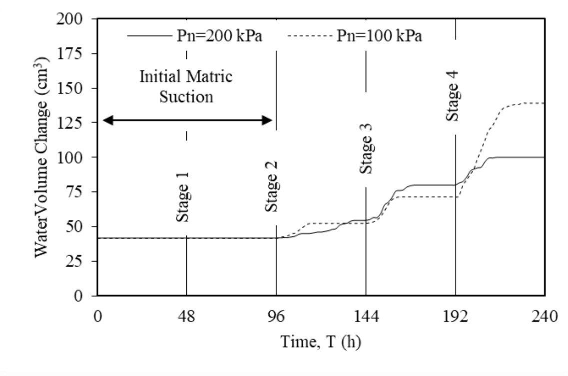

Figure 13. WVCs of G2 specimen.

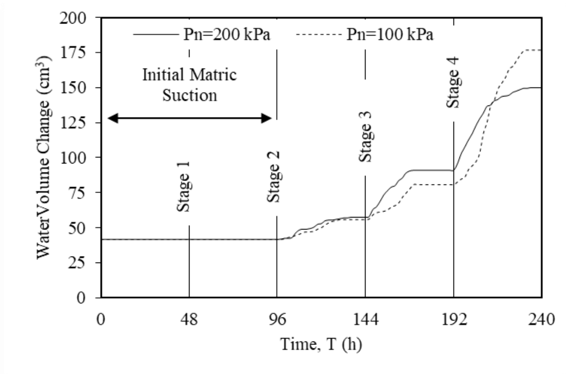

Figure 14. WVCs of G3 specimen.

In figures 12-14, from the beginning of the test until 96 hours, there is no difference in behavior of WVCs, but, after that (stage 2) there is slightly difference and increased with advancing of stages (decreasing in matric suction). The trend of G2 and G3 specimens has similar behavior of G1 specimens, as shown in figures 12-14. In lower load (Pn=100 kPa), larger WVCs are achieved due to the availability of larger void ratio. The G1 specimens have the highest WVCs because they have the biggest void ratio as mentioned in Table 1.

The cell volume changes (CVCs) were set as positive values and represent the entering of the water to the triaxial inner cell due to the decreasing in the specimen volume as a result of wetting process, as shown in figures 15-17. With progressing of the stages, there are increasing trend in CVCs for different specimens, load and time. The CVCs are increased with increasing the gypsum content. These records for G1, G2 and G3 are 38, 49 and 54 cm3 respectively under Pn=100 kPa, and under Pn=200 kPa are 65, 76 and 101 cm3 respectively.

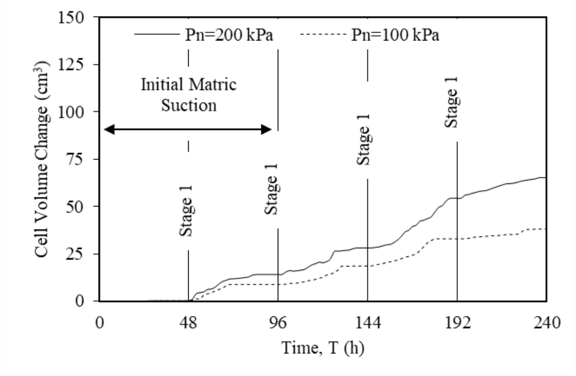

Figure 15. CVCs of G1 specimen.

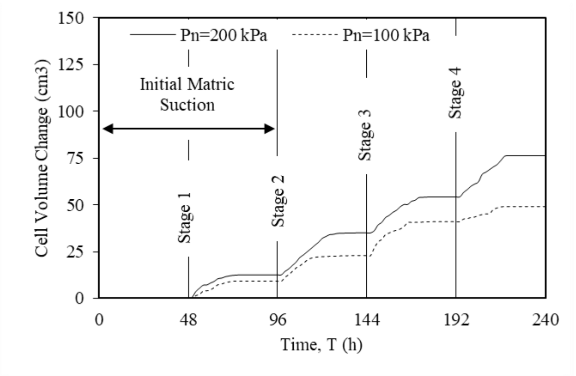

Figure 16. CVCs of G2 specimen.

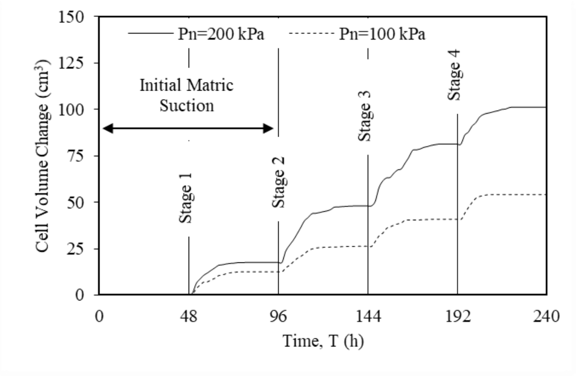

Figure 17. WVCs of G3 specimen.

There are a constant difference in CVC between both applied loads for G1 and G2 specimens, as shown in figures 15 and 16, this difference is increased with increasing the gypsum content as in G3 (figure 17).

Figures 18-20 illustrate the volumetric strains (εv) versus matric suction (ψ) for G1, G2 and G3 specimens, respectively under two various mean net stress values (Pn=100 and 200 kPa). As expected, with increasing of mean net stress, there are notable increasing in the volumetric strain. Depending on these records, when the matric suction was decreased from its initial value to 10 kPa, there was a sharp decreasing in volumetric strain for all specimens (different gypsum content).

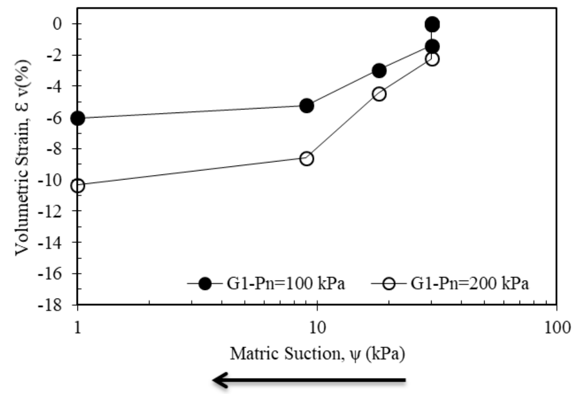

Figure 18. Volumetric strains for G1 soil specimen during wetting proses.

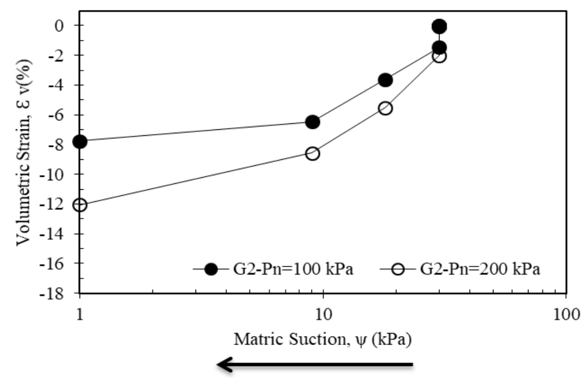

Figure 19. Volumetric strains for G2 soil specimen during wetting proses.

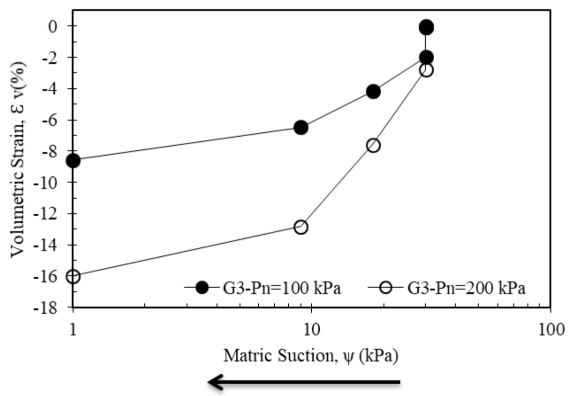

Figure 20. Volumetric strains for G3 soil specimen during wetting proses.

In G1 specimen tests, figure 18 shows that the maximum volumetric strains are 6 and 10.3 % for Pn = 100 and 200 kPa, respectively. With increasing in gypsum content (G2), there are clear increase in the volumetric strains, 7.75 % for Pn = 100 kPa and 12 % for Pn = 200 kPa, as illustrated in figure 19. This situation is certified in the case of highest gypsum content (G3), 8.5 % for Pn = 100 kPa and 16 % for Pn = 200 kPa, as presented in figure 20.

V. DISCUSSION

Table 3 shows the summary of final volumetric strains of the soil specimens from the unsaturated tests for altered conditions in wetting-path.

Generally, a clear trend of increasing in volumetric strains are achieved corresponding to increasing in gypsum content with decreasing of matric suctions. Neglecting undesirable results, approximately 20 % increase in volumetric strain with increasing of gypsum content from G1 to G2 for different load (Pn), while in G3 there are increase in percentages of volumetric strains about 37 and 49 % for load of Pn = 100 and 200 kPa, respectively. These increases may be attributed by the softening of gypsum materials that exposure to wetting process.

Table 3.
Final volumetric strains of the tested specimens in wetting-path

Pn (kPa)	ψ (kPa)	εv, (%)		
		G1	G2	G3
100	ψ 0	-1.39	-1.45	-1.99
	0.6 ψ 0	-2.94	-3.62	-4.15
	0.3 ψ 0	-5.21	-6.47	-6.45
	Saturated	-6.03	-7.75	-8.56
200	ψ 0	-2.22	-1.99	-2.77
	0.6 ψ 0	-4.43	-5.52	-7.58
	0.3 ψ 0	-8.57	-8.56	-12.83
	Saturated	-10.3	-12.04	-15.47

VI. Summary and Conclusions

There are many geotechnical and structural problems from soil wetting progress in Iraq's gypseous soils and there isn't enough information about these soil's behavior during wetting (unsaturated testing). So, there is a need to investigate the effect of degree of saturation on gypseous soils as a function of specific load and increasing loading. Therefore, a modified triaxial test device has been developed to measure the volume changes for different matric suction levels (different degree of saturations). This paper examines the influence of matric suction on the volumetric strain behavior for disturbed samples with different gypsum contents and different mean net stresses. A wetting-path procedure was adopted under four matric suction levels for two mean net stresses; Pn=100 and 200 kPa.

In this method can be concluded that there is a clear increase in volumetric strain with matric suction changes (saturation increase under specific load) and an important result is there is an enormous increase in volumetric strain with increasing of gypsum content under each specific matric suction and load.

A caution should be taken in the analysis and design of such soils by reason of gypsum presence because the rising of water table causes a volumetric strain and a settlement for the structures that are constructed on these soils. The results of this research can be used to find settlement of buildings located on gypsiferous soils in Al-Najaf in numerical and analytical methods.

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