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Variation of Matric Suction as a Function of Gypseous Soil Dry Density

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Unsaturated soil, Collapsible soils, Gypseous soil, Matric suction, Tensiometer.

ABSTRACT

Gypseous soil is one of the most problematic types of collapsible soils which is affected by many geotechnical factors. The most important factors are the effect of loading and wetting and their relation to soil density, especially when the soil at unsaturation condition. Suction pressure is the main criteria in determining the deformation behaviour of unsaturated collapsible soil when these soils distributed in arid or semi-arid region. In this study, disturbed sample of sandy soil of more than 70% gypsum content is taken from Al-Ramadi city western of Iraq. This study interested to investigate the variation of matric suction with the dry density and their effects on deformation of gypseous soil. For this purpose, a soil-model device provided with high accurate Tensiometers and Time Domain Reflectometry sensors in addition to data logger is designed and manufactured. Tensiometer sensor is used to monitor and measure the matric suction, while the Time Domain Reflectometry is used to monitor and measure the volumetric water content in the soil mass. The results of the tests showed that there is a significant effect of soil dry density on the relationship between the matric suction and water content.

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1. Introduction

Unsaturated soils are the most important types of soils used in geotechnical and geoenvironmental engineering projects such as roads, bridges and earth dams, etc., where a significant change in soil volume can be achieved by the compaction process associated with the change of moisture content, which cannot be achieved in saturated soil [1,2]. Because the degree of saturation is directly related to the voids ratio, it means that there is a significant relationship between the degree of saturation and soil density [3]. In other words, there is a significant relationship between the degree of saturation and soil suction pressure, therefore the dry density of soil is a criterion for the soil suction, especially if this soil mixed with high percentage of gypsum salts [4]. These gypsum salts cause significant problems in the soil, especially when exposed to the wetting process. Soaking or leaching the soil containing high amount of gypsum content causing dissolving of gypsum bonds between soil particles and generating large voids and cavities resulting in reduction of bearing capacity and shear strength of the soil [1,5,6,9]. The collapsible soils are normally characterized by their low density and low moisture content. The granules in this type of soils are not tightly packed and so the grains are formed in an unstable manner [9-11]. However, these grains are interlinked due to the presence of cement bonds, large soil capillary forces and many other geotechnical factors. These granules solid particles have high strength in their dry state; however, upon wetting their bonding forces will be destroyed and dissipated.

Furthermore, new soil texture will exist as a result of deformation processes. Thus the modified soil mass will consist of small grains which are directly contacted resulting in an increase in the soil density and decrease the sample volume [2]. This variation in volume appears on the soil surface in the form of a landslide. Most of these soil problems occur because of the gypsum salts which distribute between the soil grains. These salts give a name to this type of soil as " Gypseous soil" [4-6].

Gypseous soil is concentrated in arid and semi-arid regions of the world because the low annual rainfall in these areas, and therefore it is not enough to leach the gypsum salts in those soils. Gypseous soils are spread in different regions worldwide such as north of Africa, central west of Asia east of Europe and north America as shown in Figure 1, In Iraq, gypseous soils cover around 20 % of the total area especially in the western and northern parts of the country. Chemical composition of gypsum can exist in two forms: hydrated calcium sulfate ($CaSO_4.2H_2O$), and anhydrate calcium sulfate($CaSO_4$). The specific gravity of gypsum is about 2.3 [5 and 6]. Due to presence of gypseous soils in arid and semi-arid regions, it is normally formed at unsaturated state [5]. In other words, soil particles expected to have high negative pore water pressure. Upon wetting, the soil mass gradually moist until reach the equilibrium state. The behaviour of unsaturated soil is mainly related to soil suction [ψ] [1, 4, 7, 8].

Fredlund and Rahardjo [1] defined the total suction as: "the equivalent suction derived from the measurement of the partial pressure of water vapour in equilibrium with the soil water relative to the partial pressure of water vapour in equilibrium with free pure water".

In unsaturated soils, there are three components of soil suction, namely capillarity, adsorption of water on the surface of the clay minerals, and osmotic phenomena [1, 2].

Generally, for the purpose of engineering studies, matric suction (which generated from the capillarity), and osmotic suction (which generated by pore fluid chemistry and water adsorption) are the only two components of total suction. Therefore total suction can be expressed as:

$$\psi = (u_a - u_w) + \varphi_s \quad (1)$$

Where $(u_a - u_w)$ is the matric suction, (u_a) is pore air pressure, (u_w) is pore water pressure and φ_s is osmotic suction.

In other word, the matric suction can be defined as a difference between the pore air pressure (u_a) and the pore water pressure (u_w). In geotechnical engineering field, pore air pressure can be considered equal with atmospheric pressure and therefore it can be ignored $(u_a = 0)$, and (φ_s) is the osmotic suction, being the result of chemical imbalance between the pore water in the soil volume under consideration and an external source of water [1]. Its value can also be ignored in geotechnical engineering applications being very few compared to matric suction($\varphi_s = 0$).

The aim of this paper is to discuss the relationship between the collapse deformation and the matric suction pressure when the soil dry density varies under constant applied stress by using a multi-steps wetting process.

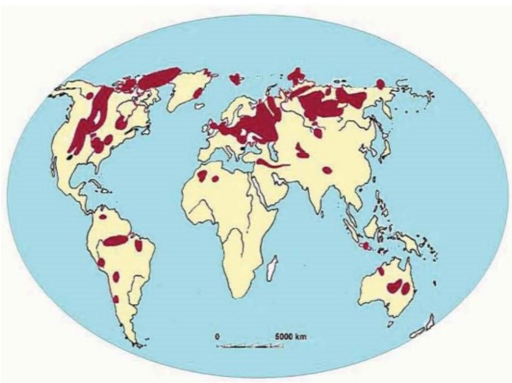

Figure 1: Distribution of gypseous soil in the world (after FAO, 1990) [12]

2. Characteristics of the Soil Used

The disturbed soil samples were brought from a site of highly gypsum content located in a semiarid to arid region nearby Al-Anbar University within Al-Ramadi city in western Iraq. The soil can be described as dense to very dense reddish brown fine to medium SAND with high amount of gypsum content in the form of white salts and crystalline particles. The main physical and chemical properties of the investigated soil are shown in Table 1.

Table 1: Summary of physical and chemical soil properties

Property	Value
Natural water content [%]	1
Atterberg's limits [%]	No plasticity
Specific gravity:	2.37
by Water [-]	2.35
by Kerosene [-]	
In place dry density [g/cm^3]	1.3
Relative density [%]	82
Natural void ratio [-]	0.81
Standard compaction test:	1.57
Maximum dry density [g/cm^3]	15.5
Optimum moisture content [%]	
Particle size analysis:	4.5
Cu [-]	1.4
Cc [-]	
Passing sieve (0.075mm), by (dry, water, kerosene) [%]	4.7,17.6, 3.3
Soil classification	
TSS [%]	SP
SO_3 (acid) [%]	11.5
Gypsum content [%],	34.5
(Al-Mufty and Nashat, 2000)	70

3. Soil-Model Device

In order to investigate the volume change, matric suction, and critical collapse zone; special soil-model device was designed and manufactured as shown in Figures 3 and 4. The soil-model device has the following technical details: rigid steel material of 1.5 cm (thickness), inner dimensions are 30.2 cm (length), 30.2 cm (width), 31.0 cm (sample height) and 2.0 cm (thickness of rigid plate cover). The soil-model device is provided with graded gravel filter layer of 0.5-1.0 cm (particle diameter range) and 2.0 cm (filter height). The purpose of this layer is to insure of the uniform distribution for the moisture through the soil mass and to flash the air bubbles under the soil sample.

The filter layer includes two opposite valves used as a water inlet and flashing of air bubbles. In addition, many valves have been provided in the horizontal and vertical directions of the model in order to mobilize the sensors to the desired level of soil. The first sensor is highly sensitive Tensiometer sensor type (EQ3 equitensiometer) to measure the matric suction of the soil as shown in Figure 2a, and second sensor is Time Domain Reflectometry sensor (TDR) type (ML3 Theta Probe) to measure the volumetric water content of the soil as shown in Figure 2b. These two sensors are connected to the data logger type (GP1 Data Logger) as shown in Figure 2c. The applied axial loading was controlled by using an automatically rigid loading frame with a loading capacity of 200 kN. The soil settlement was monitored by using two sensitive dial gauges with an accuracy of 0.002 mm.

4. Test Method

The test method can be summarized into following steps:

1. Preparation of the soil samples inside Soil-Model device by static compaction the sample in three layers according to the following initial boundary conditions: Void ratios (e): 1.1, 0.81 and 0.47; Dry densities: 1.1, 1.3 and 1.6 g/cm^3; Water content: 0 %; Degree of saturation: 0 % and Initial suction: 139,000 kPa.
2. The Time Domain Reflectometry (TDR) and Tensiometers (TS) sensors were previously fixed in the mid position of the Soil-Model device. However, care must be taken in order to ensure that the sensors are safe during compaction process and the good contact is occurred between the soil and sensors.

3. Application the vertical stress of 25 kPa by using of pressure control machine and measurement the deformation by using the two dial gauges of accuracy equal to 0.002 [mm].
4. Reduction of matric suction by stepwise increasing of the water content in the soil mass.
5. Increase the moisture content of the soil mass (i.e. from unsaturated state towards saturated state) was carried out by fully saturated the gravel filter layer through the soil-model valves at the bottom side without application of hydraulic gradient (see Figure 2). The moisture content was raised in soil skeleton based on capillary forces and suction pressure.
6. The matric suction and the volumetric water content ($V.wc$) were recorded during the test by using high accurate Data logger (GP1) until reach to fully saturation at very low range of matric suction.
7. Calculate the gravimetric moisture content by using the equation below:

$$G.w(\%) = V.w(\%) * \frac{\rho_w}{\rho_s} \qquad (2)$$

Where:- $V.w$: Volumetric water content, ρ_w= Water density= 1 g/cm^3, ρ_s: Soil density.
8. Calculate the void ratio using the equation:

$$e = \frac{H*A*Gs*\rho_w}{Ms} - 1 \qquad (3)$$

Where: - H: Sample height, A: Sample cross sectional area, Gs: Specific Gravity, Ms= Soil sample mass.

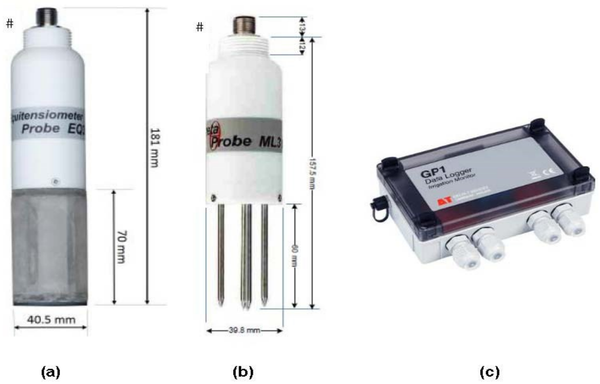

Figure 2: Sensors used for measurement the matric suction and volumetric water content: (a) Tensiometer Type EQ3, (b) TDR Type ML# and (c) Data Logger Type GP1

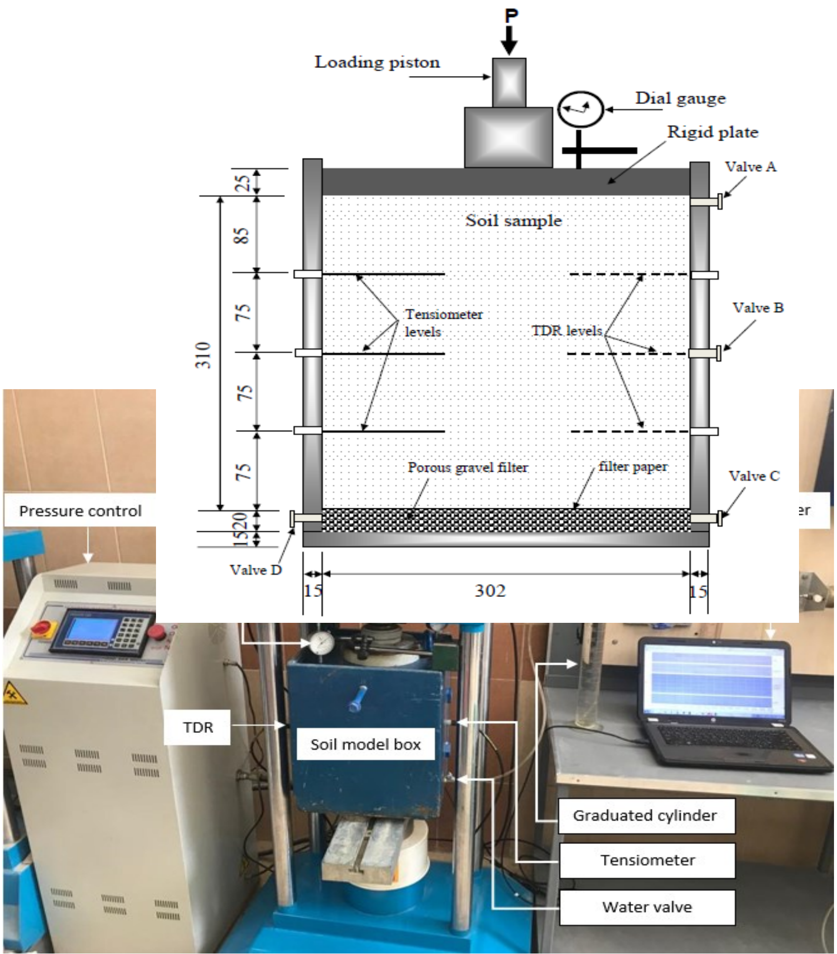

Figure 3: Device (all **Sketch of Soil-Model with loading and measuring system dimensions in mm)**

Figure 4: Soil-Model Device with loading and measuring system

5. Results and Discussion

In this section, the results of volume change under suction control at different initial dry densities will be presented. The relationship between the soil suction and void ratio, volume change, gravimetric water content and degree of saturation are shown in Figures 5 to 9 respectively. From Figures (5a, 5b and 5c) it can be observed that the void ratio was slightly reduced with a significant decrease in soil suction until reaches to the zero suction value. This behaviour is due to the distribution of moisture through the soil mass from gravel filter layer during multi-steps wetting processes. Increasing of moisture content by gradually rising of water will result in more dissipation of capillary forces and lead to more deformation and change in void ratio. Comparison between the results of the three curves with the same values of suction pressure is shown in Figure 6. It can be noticed that the soil volume changes at the three initial dry densities are of the same trend. Moreover, converge in the shape of dry density curves for the three tests were observed at high suction pressure range until reach to suction pressure of 1000 kPa. After that significant differences between these curves were noticed until reach to saturated state of zero suction. This behavior associated with relative reduction in soil volume change. This behavior can be related to the fact that the soil with low density has a large voids ratio. When the applied pressure starts, the air voids are expelled, which in turn leads to the need for a large amount of water to reach the saturation condition as shown in Figure 7. This, in turn, results in an increase in the time period of the test, and the continued applied pressure to the soil sample for a longer period, resulting in a significant change in volume as shown in Figure 9. Figures 7 and 8 show the relationship between the soil suction versus gravimetric water content and degree of saturation respectively. In both relationships and for all initial dry density, it can be observed that at high suction range (i.e. from high initial value to approximate 5000 kPa) an insignificant change in the values of water content and degree of saturation were observed.

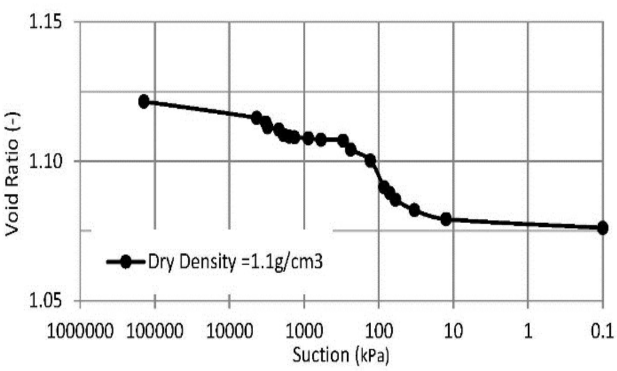

Figure 5a: Variation of suction with void ratio (Dry density=1.1 g/cm3)

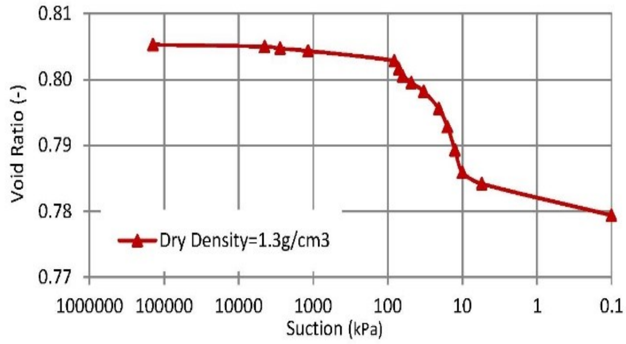

Figure 5b: Variation of suction with void ratio (Dry density=1.3 g/cm3)

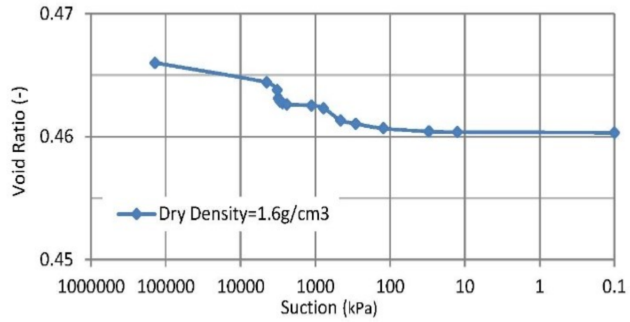

Figure 5c: Variation of suction with void ratio (Dry density=1.6 g/cm3)

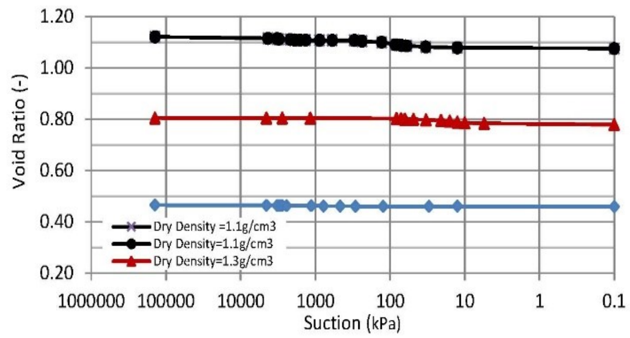

Figure 6: Variation of suction with void ratio

This behaviour can be attributed to that the soil mass with high matric suction range lies with boundary effect zone and below the air entry value of the soil water characteristics curve.

Moreover, at medium and low range of matric suction sharp reduction in water content and degree of saturation were recorded especially for low dry density sample until reach to zero suction. Dissipation of suction pressure can be related to the fact that all capillary forces were destroyed when the soil near the fully saturated state. These results confirm with that obtained by Al-Obaidi [4]. Figure 9 illustrates the relationship between soil volume change and soil suction. It can be observed that for the same suction value, the volume change in soil mass varied significantly during the test in case of low dry density sample. While when the initial dry density was higher, the variation in volume change was relatively small. In general, the volume change in soil samples for low, medium and high initial dry density has the same trend, where the increasing in volume change was corresponding to the decreasing in suction pressure. Nevertheless, low dry density (i.e. 1.1 g/cm3) exhibited considerable deformation especially after the air entry value (i.e. at suction pressure of about 5000 kPa). On the other hand, high initial dry density (i.e. 1.6 g/cm3) shows more stable structure mass due to the capillary forces still resistant the reduction in suction pressure irrespective of its very low range values.

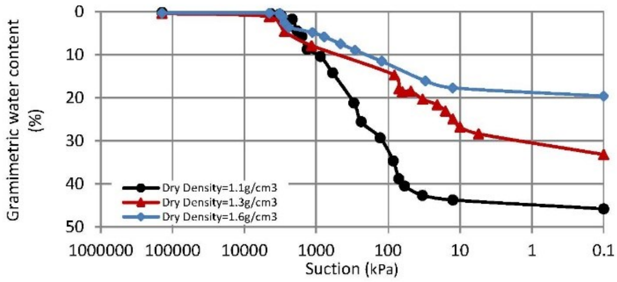

Figure 7: Variation of suction with gravimetric water content

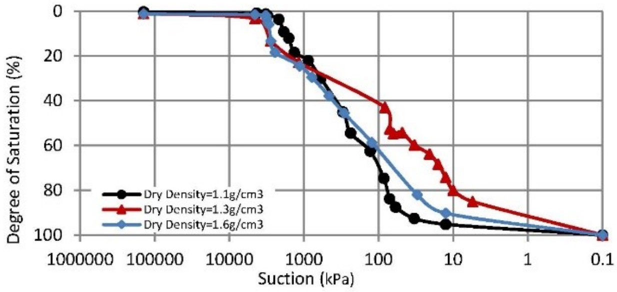

Figure 8: Variation of suction with degree of saturation

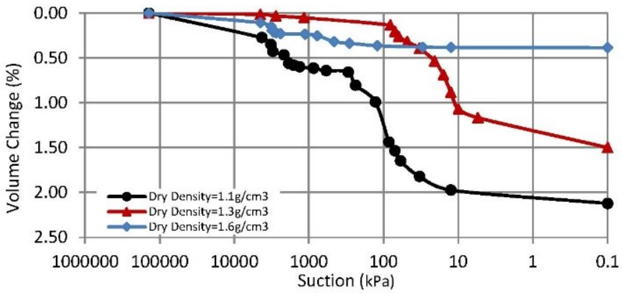

Figure 9: Variation of suction with volume change

6. Conclusions

The conclusions of the tests results can be summarized as follow:

1. The void ratio of gypseous soil decreases with decreasing of soil suction. The reduction magnitude depends on the value of initial dry density.
2. For the same soil suction, the volume change in soil mass has a significant values at low dry density sample. While at high initial dry density, the variation in volume change was relatively small. The volume changes in soil samples for low, medium and high initial dry densities have the same trend, where the increasing in volume change was corresponding to the decreasing in suction pressure. Nevertheless, the initial dry density is the function of collapse deformation.
3. At high suction range, an insignificant change in the values of water content and degree of saturation was observed. While at medium and low range of matric suction, a sharp reduction in water content and degree of saturation was recorded especially for low dry density sample until reaching zero suction. Thus, air entry value is the main factor for soil dry density and volume of water in the soil mass.
4. Al-Ramadi gypseous soil has low volume change and large strength at highest level of soil suction (i.e. more than 5000 kPa) were cemented by significant capillary forces, however the cementing bonds will be vanished at saturation state of zero suction.

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