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SUCTION VARIATION OF NATURAL AND TREATED UNSATURATED GYPSEOUS SOILS DURING WETTING

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Abstract

The current work is directed to study the variation of suction with time and soil water characteristics curve (SWCC) for natural and treated gypseous soil treated with two types of additive (lime and silica fume) compacted at different initial degrees of saturation S_0 = 20 and 50 %. Soil subjected to wetting in an upward direction. Three types of gypsum soils were experimented with different gypsum content 15, 35, and 60 % taken from various sites in Salah Al-dean government, Iraq. The main results show that the air-entry value, residual values, and the time required for the entire saturation stage increases with increasing gypsum content and treatment with lime and silica fume and they for soil treated with silica fume are greater than for soil treated with lime. The rate of flow for soil treated with silica fume is less than that of soil treated with lime. The treated soil is more effective in increasing the time required for the entire saturation stage and decreasing the rate of flow when compacted at an effective degree of saturation S_0 = 50 %.

Keywords:

Gypseous soil;
Suction pressure;
Soil water characteristics curve;
Lime;
Silica fume.

1 Introduction

There are several soils all around the world that collapse (experience significant settlement) when unusually subjected to amounts of water. Collapsible gypseous soil is one of the wide varieties of problematic soils. The gypseous ground can be found in dry and semi-arid areas. Here, gypsum deposits are common such as in Iraq. Gypseous grounds are considered as collapsible or metastable soils, considered any type of unsaturated soil, which reveals a radical re-arrangement of soil particles and is disposed to a significant change in volume. Collapses occur when soils are wetted with water. This may additionally occur if soils are socked under loading [1, 2]. Gypsum is a hydrated calcium sulfate mineral $CaSO_4.2H_2O$ having an intermediate solubility of 2.6.g/l at 25 ºC [3]. When the soil is dry, the gypsum in the soil structure functions as cement. Studying the properties of unsaturated soil with gypsum is a challenging problem in many geotechnical engineering applications, such as dams, strata under pavement, and foundations [4].

The field of soil mechanics in general, could be divided into a portion dealing with saturated soils and another dealing with unsaturated soils. Due to fundamental distinctions in their nature and engineering behavior, saturated and unsaturated soils must be distinguished from one another. In unsaturated soil, there are more than two phases, and the pore-water pressure is negative compared to the pore-air pressure. The main geotechnical problems connected to these soils are that when the soil gets wet, the pore pressure decreases, the effective stresses are concentrated, volume changes, and decreasing the soil's shear strength. Moreover, water can soften the soil particles' bonds, enabling denser packing. Negative pore-water pressures and ability desaturation could be influenced any soil near the ground surface that is present in a dry environment. The processes of remoulding, excavating, and recompacting soil also produce unsaturated material. These materials comprise a significant proportion of soils that are typically challenging to analyze within the framework of traditional soil mechanics. [5].

Suctions in unsaturated soils may vary greatly (from zero to 10^6 kPa), as a result of reactions to imposed weather conditions. If the suction pressure is considered, it is possible to understand better the engineering behavior of soils within an unsaturated state [6]. Suction stress plays an obvious function in the unsaturated soils' behaviors, shear strength, permeability, and volume change. The total amount

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of free energy present in a unit volume of soil water is called soil suction, which includes, matric suction, and osmotic suction [6].

Matric suction represents the variance between pore air pressure u_a and pore water pressure u_w. Osmotic suction results from variances in salt condensation in pore water compared to pure water. In general, it is the effect of mineral salt. The sum of matric and osmotic suction yields the total soil suction. Matrix suction can keep the meta-stable structure and strong intergranular interactions between the particles in unsaturated soils. These connections are water-sensitive, and suction reduces as moisture content rises. They gradually collapse under water, usually under the influence of an outside force [7]. The relationship between the matric suction and the degree of saturation (volumetric water content) is described as the "soil-water characteristic curve" (SWCC) or "soil-water potential". Many of soil property functions are evaluated from SWCC in unsaturated soil. In addition, SWCC is usually used for evaluating the shear strength and permeability of unsaturated soils [8].

For many geotechnical applications, such as layers under pavement, highways, and infrastructures, chemical stabilization of gypseous soils is essential to avoid damage from gypsum dissolution. Many researchers have investigated the variation suction during wetting on the collapse of natural gypseous soil behavior.

Al-Obaidi et al. [9] conducted a model test to study the suction variation with time and the wetting effect on the volume change of unsaturated gypseous soil. The study showed that increasing the initial dry density γ_d increases the time required to attain the saturation stage (zero suction). Fattah et al. [10] examined the collapse potential (CP) associated with the variations in soil suction and the effect of the initial load on soil suction by using the pressure cell. The preliminary investigation showed that the CP proportionally increases as the initial void ratio increases. Karim et al. [11] study the collapse of gypseous soil by employing a developed soil model and multi-step wetting. According to the test results, a significant collapse deformation happened when the matric suction was reduced and the void ratio was considerably reduced as many steps of wetting reduced matric suction. Al-Obaidi et al. [12] studied the variation of suction with the dry density and their effects on the collapse of gypseous soil. According to the test results, the void ratio of gypseous soil decreases as soil suction decreases. The amount of depletion depends on the initial dry density.

However, more research needs to be mainly directed at understanding the behavior of unsaturated treated gypseous soils when subjected to wetting. Therefore, this study proposes to simulate the behavior of treated gypseous soil in the framework of unsaturated soils. Therefore, the work is oriented to predict the variation of suction with time and water characteristics curve SWCC properties for natural and treated gypseous soil. Several studies considered the effect of treatment, curing time, and temperature on SWCC such as [13-15]. This study estimates the SWCC by using a large model apparatus for gypseous soils compacted at their natural degree of saturation treated by two types of additive when soil is subjected to wetting in an upward direction. A block of porous gypsum sensors (Watermark sensor) is located at a different depth within the soil model to measure the SWCC. These sensors are sensitive to the chemical formation of the soil, pore size distribution, degree of saturation, and suction pressure. In addition, the rate of flow was determined from the model to show the effect of variation in gypsum content, treated materials (lime and silica fume), and initial degrees of saturation on the rate of flow.

2 Experimental program

The gypseous soil utilized in the present study is naturally disturbed, and samples were taken from three separate sites in Salah Al-Dean governorates, Iraq. Soil-A from Baiji City, north of Tikrit City, with medium gypsum content 15 %, soil-B from Al-Deoum discrete, west of Tikrit City with medium gypsum content 35 % and soil-C from Tikrit University, north of Tikrit city with high gypsum content 60 %. A number of 18 model tests were conducted to perform the study program. Two types of additives would be used to enhance gypseous soil's properties: lime (one of the most effective, cheapest, and economical materials [16]) and silica fume (micro materials have significant progress as an interdisciplinary field). Because of the difficulty to achieve maximum dry density in the field, the soil compacted at its natural dry unit weight to achieve approximately a relative density D_r of 78 % for the three soils. Two initial degrees of saturation S_0 were used to compact the soil, (20 %, which represents the field degree of saturation) and (50 %, which represents the effective degree of saturation). The percentage of lime and silica fume was 4 % for all types of gypseous soil. The optimum percent of additive 4 % and the effective degree of saturation 50 % (the initial degree of saturation above, at which

negligible collapse potential exists) were determined according to the results collapse potential test ASTM D-5333.

2.1 Soil properties

Each soil's physical, classification, and chemical characteristics were determined using standard tests, and the main results are described in Table 1. The testing program for soil was conducted at "Soil Mechanics Laboratory" at the University of Tikrit. The grain size distribution curve is shown in Fig. 1. Gypsum content was calculated using the hydration method, which depends on weight loss, by heating the gypseous soil. Weight of loss is a result of gypsum dehydration [17]. Al-Mufty et al. [18] have improved this approach. The properties of lime and silica fume are shown in Table 2.

Table 1: Physical and chemical properties of the used soils.

Index Property	Soil-A	Soil-B	Soil-C	Specification
Gypsum Content [%]	15	35	60	
Specific Gravity *Gs*	2.57	2.47	2.37	ASTM D-854
Natural Water Content [%]	4.5	4.64	5.57	ASTM D-2216
D10 [mm]	0.121	0.095	0.075	
D30 [mm]	0.246	0.182	0.170	
D60 [mm]	1.18	0.357	0.559	
Liquid Limit (L.L)	N.L	N.L	N.L	ASTM D-4318
Plastic Limit (P.L)	N.P	N.P	N.P	ASTM D-4318
Coefficient of uniformity *Cu*	9.75	3.763	7.464	ASTM D-4254
Coefficient of curvature *Cc*	0.424	0.972	0.692	ASTM D-4254
Maximum dry unit weight [kN/m^3]	17.5	16.7	15.2	ASTM D-698
Minimum dry unit weight [kN/m^3]	12.2	12	11.6	ASTM D-4254
Field dry unit weight [kN/m^3]	16.0	15.4	14.24	ASTM D-4531
Classification according to USCS	SP	SP-SM	SP-SM	ASTM D-2487
Classification according to ESCS	SaM	SaP	clSaM	EN ISO 14688-2:2018
Friction angle, φ in [º]	35.7	36.1	37.7	ASTM D-3080
Cohesion *c* in [kPa]	15.3	17.3	18.1	ASTM D-3080
Total sulphate content SO_3 [%]	27.3	46.61	65.2	
pH value	8.05	8.03	7.93	

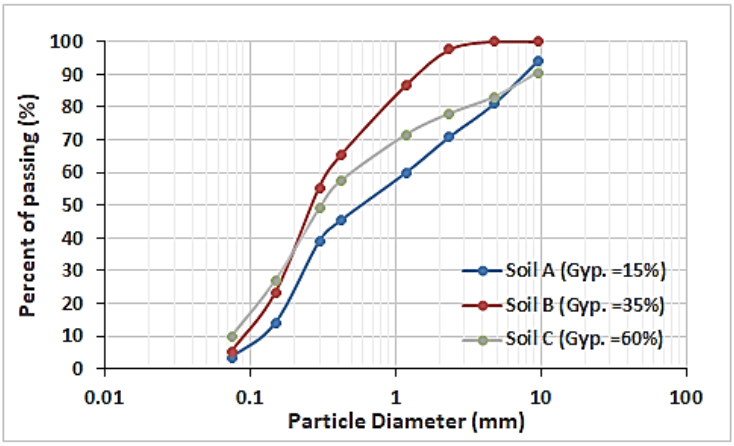


Fig. 1: Particle size distribution of the used soils.

Table 2: The physical and chemical properties of the used lime and silica fume.

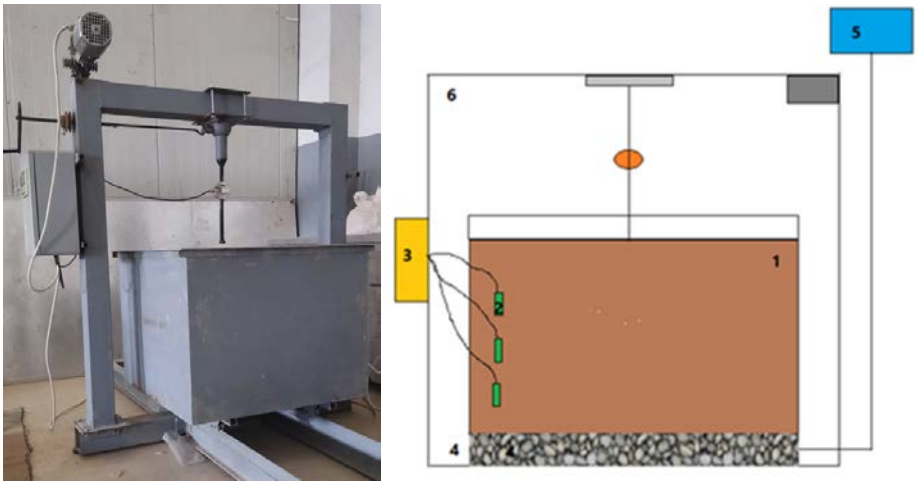
Properties	Lime	Silica fume
Color	White solid	grey black powder
Specific gravity	2.3	2.1
Bulk density [kg/m^3]	636	300
Surface area [m^2/kg]	576	20000
SiO_2 [%]	11.36	93
Al_2O_3 [%]	0.16	1

2.2 Soil model device

A model device was manufactured to achieve the required information for the study. Fig. 2a shows the manufactured apparatus model. Fig. 2b has presented a schematic diagram of the experimental setup. The system formation of the following accessories:

1) Soil box 800*800*700 mm.
2) Irrometer watermark sensor models 200SS-15.
3) Data logger model 900M.
4) Filter material.
5) Saturation system.
6) Metal frame.

The data logger uses the Water Graph 3.2 software (WG3). It is possible to automatically take one reading for every minute per day. The computer reads the recorded data that send to it.



a) The manufactured apparatus model. b) Diagram of installed sensors and saturation system.

Fig. 2: Soil model device.

2.3 Model test preparation

The gypseous soil was compacted in the model, with its field dry unit weight γ_d and water is added to achieve a different initial degree of saturation 20 % and 50 %. Every 15 kilograms of soil was mechanically mixed by hand with the equivalent amount of additive and water. For untreated soil, water is added to the soil and left for 24 hours inside a tight plastic bag to obtain a homogenous mixture while the mixture was left for one hour for a mellowing period for treated soil, and then the compaction was done. The box depth of 700 mm is divided into 7 layers, each layer 100 mm in height. The first layer comprises the filter material that allows water to flow freely without eroding the soil. Geo-mesh layers were positioned above the filter material to prevent the soil from mixing as shown in Fig. 3a. An especially manufactured hammer was employed to densify soil in the box to the desired density, as shown in Fig. 3b. A specific insertion tool installs the watermark sensors CAT No. 1017 at depths 100 mm, 200 mm, and 300 mm from the model surface as shown in Fig. 3c, d. Then the soil inside the box was coated with a double layer of nylon for seven days for curing processes at 25 ºC. The saturation procedure concerned full saturation till the three-sensor readings approached zero. The saturation was

carried out by allowing water to flow through the soil in a model in an upward trend (from the lower base) at a discharge of 100 ml/min with a steady rise and total head of 1.5 m.

3 Discussion

Soil water characteristics curve SWCC and variations of suction pressure with time were recorded by the intromission of three sensors. The maximum suction reading that could be recorded by the watermark sensors is 239 kPa. So, the higher suction value (greater than 239 kPa) corresponding to an initial degree of saturation of 20 % was calculated by the filter paper method ASTM D-5298. Because the sensors at a depth of 300 mm are close to the base of the soil box, the water reaches it faster than that at a depth of 100 mm and 200 mm.



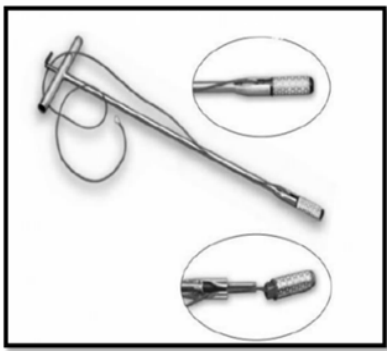
a) Arranging of filter material andgeo mesh.



b) A manufactured hammer for compaction.



c) Inserting of a sensor into the borehole.



d) Insertion tool CAT No. 1017.

Fig. 3: Model preparation.

3.1 Effect of gypsum content

Fig. 4 shows the SWCC for the three natural gypseous soil. It could be seen that the SWCC for soil is arranged according to its gypsum content. The soil having a high percentage of gypsum is higher than the SWCC of the other two soils, which have a lower percentage of gypsum. In addition, both air-entry value and residual value increase with increasing gypsum content as shown in Table 3. The increase in the water-holding capacity of soil samples as the gypsum content increases could be attributed to the presence of dissolved salts. Moreover, the vapour pressure of water over a solvent's flat surface is lower than that of pure water. Therefore, the total suction pressure increases with increasing osmotic suction causing decreasing in relative humidity with increasing dissolved salts in the soil's pore water [13, 19]. Fig. 5 shows the variation of matric suction with time. The results show that the time required for a drop in suction pressure reading (reaching the entire saturation case) increases with increasing gypsum content for both an initial degree of saturation 20 and 50 %. This behavior could be attributed to suction's effect on gypsum soil's permeability. Thus, as suction pressure increases, the unsaturated coefficient of permeability decreases, affecting the time required to reach the full saturation case. Therefore, the unsaturated hydraulic conductivity can interfere with the SWCC in such a case, and estimation procedures are generally used [8].

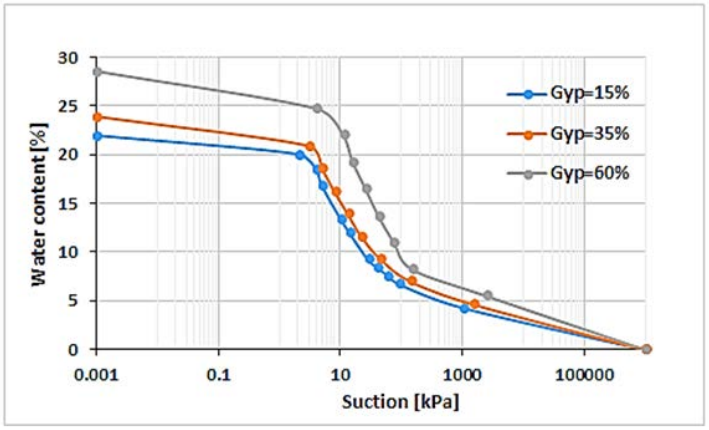
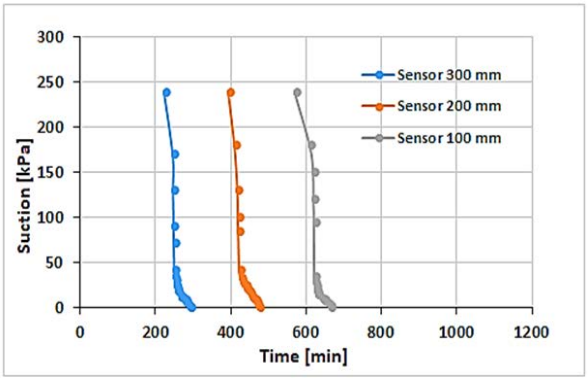
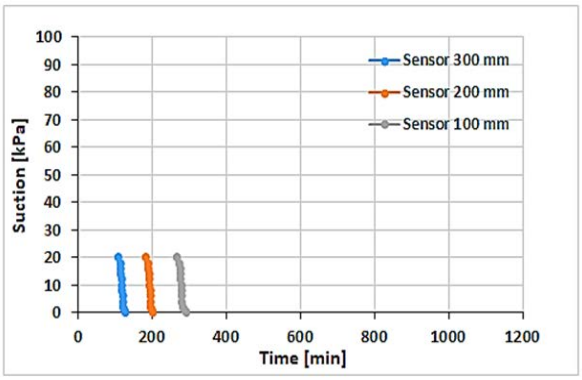


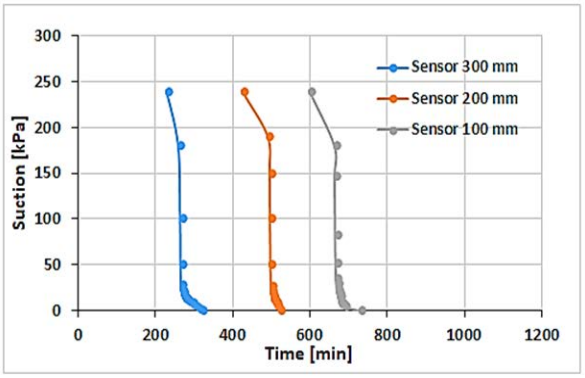
Fig. 4: Soil water characteristics curve (SWCC) for natural gypseous soil.



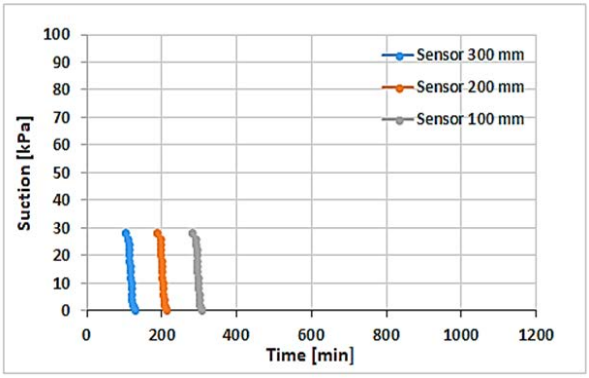
a) Soil-A (S_0 = 20 %).



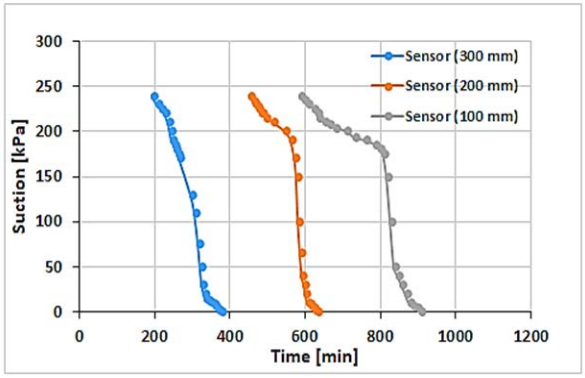
b) Soil-A (S_0 = 50 %).



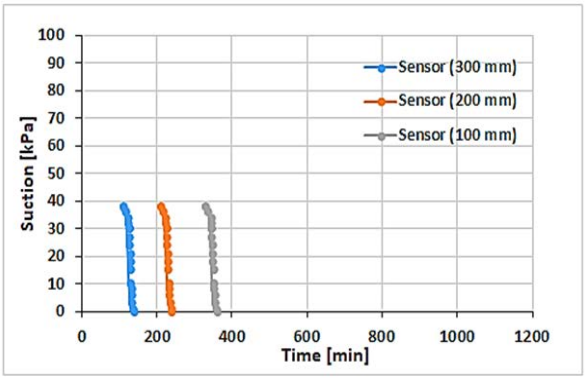
c) Soil-B (S_0 = 20 %).



d) Soil-B (S_0 = 50 %).



e) Soil-C (S_0 = 20 %).



f) Soil-C (S_0 = 50 %).

Fig. 5: Time-matric suction variation for natural soil.

3.2 Effect of treatment with lime and silica fume

Figs. 6-8 show SWCC for natural and treated gypseous soil with lime and silica fume compacted at their natural degree of saturation. It could be seen that the SWCC of treated soil was shifted right horizontally compared with the SWCC for untreated soil. For soil treated with lime, the formation of pozzolanic material reduces the pores' size. These cementitious components interact with the soil and shrink its pores. The materials created by pozzolanic reactions alter the microstructural characteristics of the treated soils [20, 21].

For soil treated with silica fume, silica fumes filled the voids in the soil sample and enveloped the surrounding soil particles. Then, silica fume particles that have accumulated in the pore space between the soil grains react to generate hydration products around the soil grains. Calcium compounds, which are common in gypsum soil and combine with water molecules to produce Ca_2^+ ions. Calcium silicate hydrate gels $CaSiO_3 \cdot H_2O$ are produced by the reaction of the active silica with calcium hydroxide. It was observed that this reaction made the material stronger and more brittle [22]. According to the above explanations, the air-entry value and residual value for treated soil are greater than for untreated soil, as shown in Table 3. Air entry value increased by 100, 133, and 150 % for soil treated with lime while increased by 150, 200, and 225 % for soil treated with silica fume. Residual value increased by 39, 60, and 70 % for soil treated with lime while for soil treated with silica fume, residual value increased by 54, 73, and 77 % for the three soil respectively soil A, B, and C.

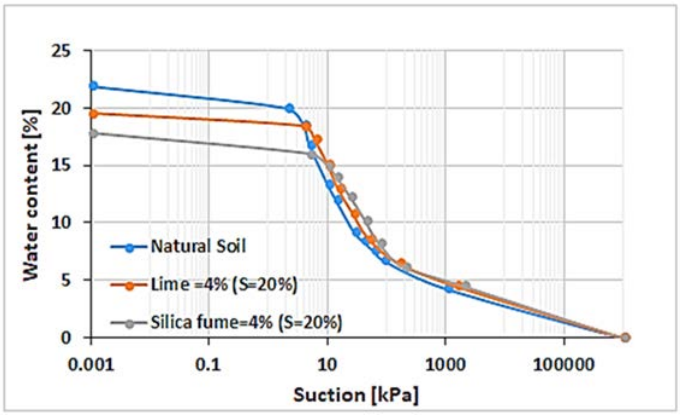


Fig. 6: Soil water characteristics curve SWCC for natural and treated gypseous soil (Soil-A).

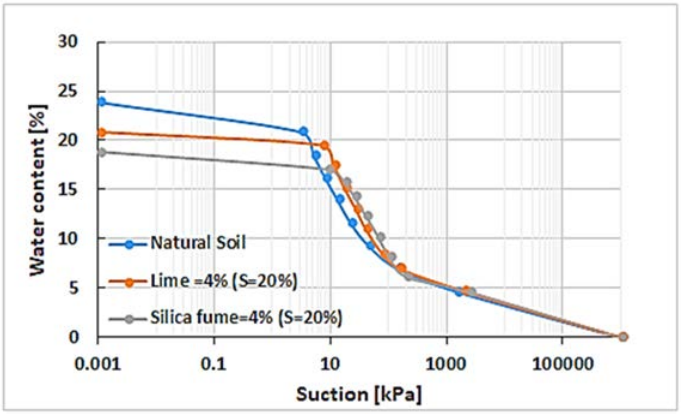


Fig. 7: Soil water characteristics curve SWCC for natural and treated gypseous soil (Soil-B).

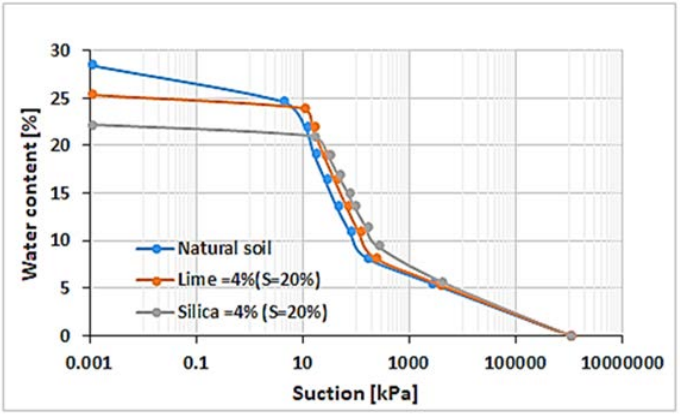
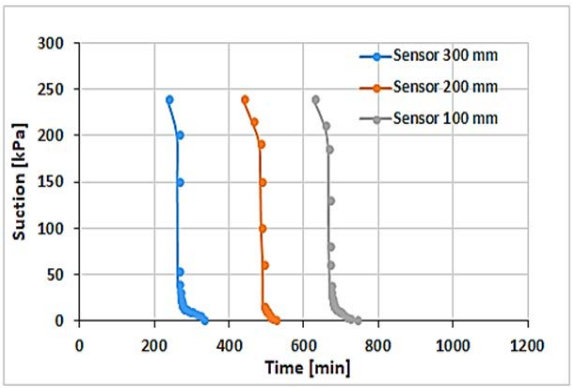


Fig. 8: Soil water characteristics curve SWCC for natural and treated gypseous soil (Soil-C).

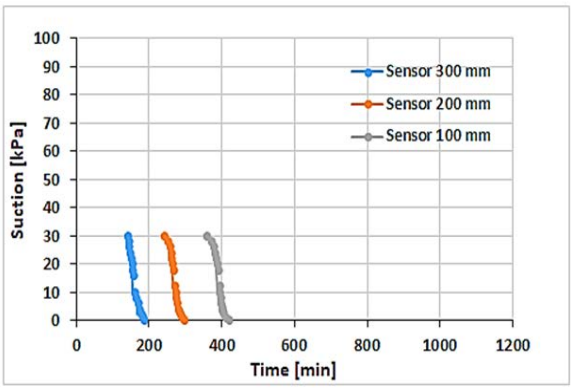
Table 3: Determination of Air- entry value and residual value for treated and untreated soils.

Soil	Cases	Air-entry value [kPa]	Residual value [kPa]
Soil-A	Natural soil	2	65
Soil-A	Soil treated with lime	4	90
Soil-A	Soil treated with silica fume	5	100
Soil-B	Natural soil	3	75
Soil-B	Soil treated with lime	7	120
Soil-B	Soil treated with silica fume	9	130
Soil-C	Natural soil	4	135
Soil-C	Soil treated with lime	10	230
Soil-C	Soil treated with silica fume	13	238

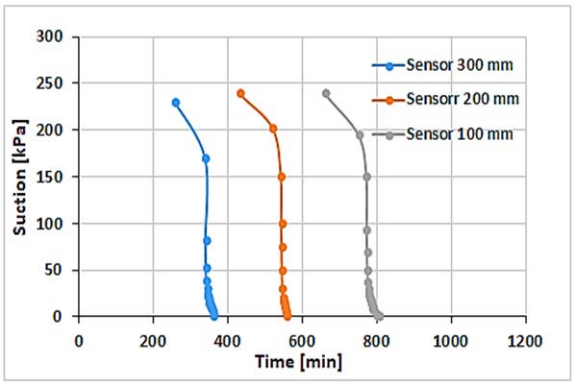
Fig. 9 shows the variation of matric suction reading with time for lime-treated soil, while Fig. 10 shows the variation of matric suction reading with time for silica fume-treated soil compacted at an initial degree of saturation of 20 and 50 %. It could be noticed that the time required for a drop in suction pressure reading (reach entire saturation case) for treated soil is greater than that for untreated soil. The percent of the increasing time for soil treated with lime compacted at a natural degree of saturation S_0 = 20% was 13, 11, and 14% while the percent of increasing time for soil treated with silica fume was 20, 23, and 22%. Whilst the percent of the increasing time for soil compacted at an effective initial degree of saturation S_0 = 50% was 40, 51 and 57 % for soil treated with lime while the percent was 55, 57 and 70 % for soil treated with silica fume for the three soil respectively, soil A, B, and C.



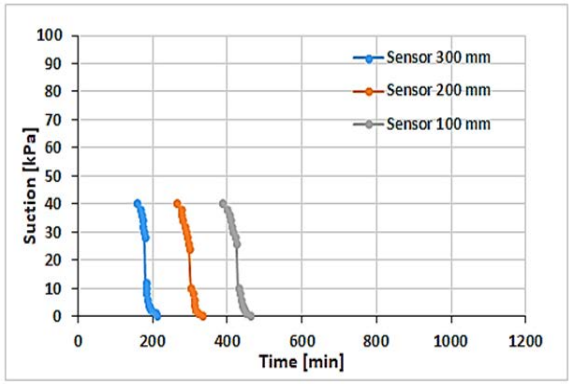
a) Soil-A (S_0 = 20 %).



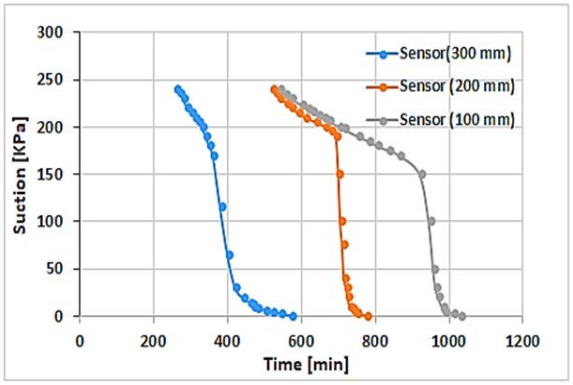
b) Soil-A (S_0 = 50 %).



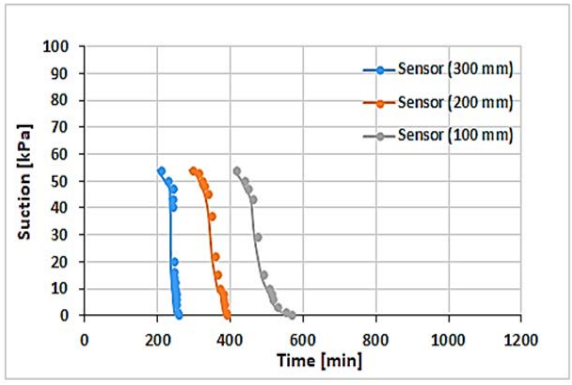
c) Soil-B (S_0 = 20 %).



d) Soil-B (S_0 = 50 %).

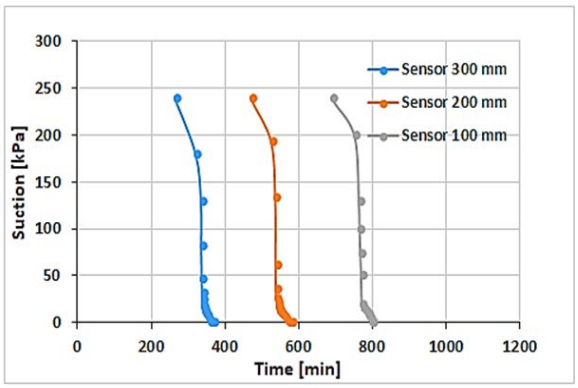


e) Soil-C (S_0 = 20 %).

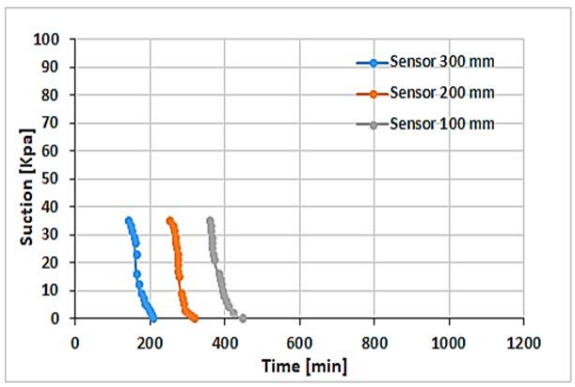


f) Soil-C (S_0 = 50 %).

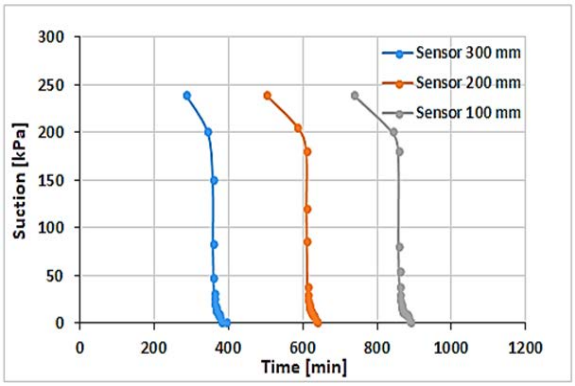
Fig. 9: Time-matric suction variation for lime-treated soils.



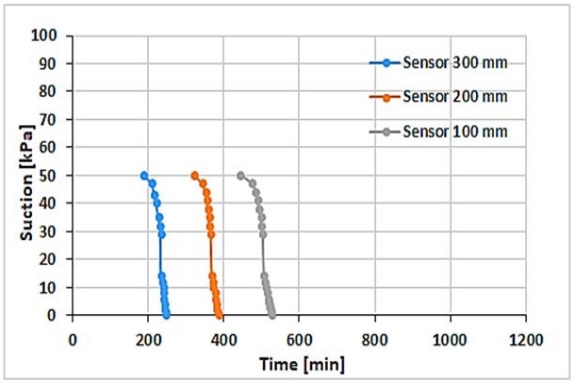
a) Soil-A (S_0 = 20 %).



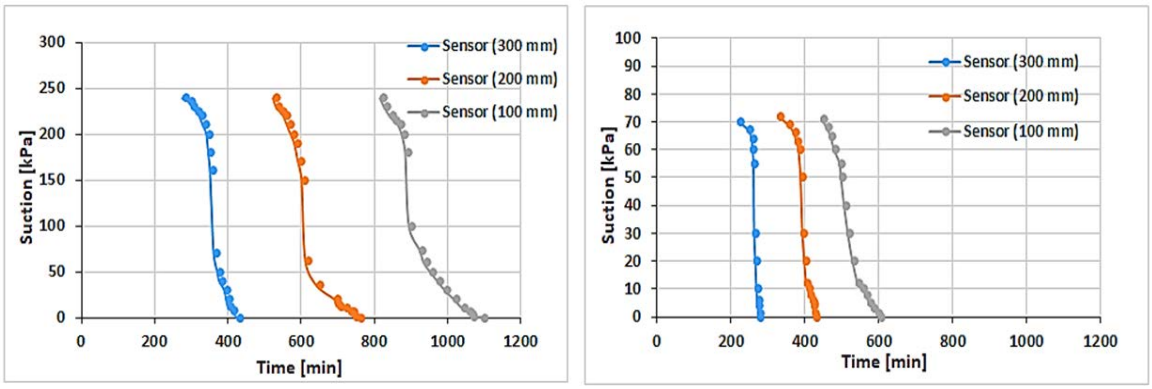
b) Soil-A (S_0 = 50 %).



c) Soil-B (S_0 = 20 %).



d) Soil-B (S_0 = 50 %).



e) Soil-C (S_0 = 20 %). f) Soil-C (S_0 = 50 %).

Fig. 10: Time-matric suction variation for silica fume-treated soils.

Fig. 11 shows the variation of time required for the entire saturation stage for treated and untreated soil with a variation of gypsum content. It could be noticed that the time required for a drop in suction pressure reading for soil treated with silica fume is greater than that for soil treated with lime. This behavior could be attributed to the large surface area of silica fume (compared with that for lime), which causes block more voids through soil Skelton. In addition, silica fume could fill up the space between soil particles, thus reducing the voids in soil samples. Furthermore, the small size of silica fume particle aid in overlapping soil particles, causing voids clogging and decreasing the hydraulic conductivity.

Fig. 12 shows the variation in the rate of flow with gypsum content for treated and untreated gypseous soil. The rate of flow for treated soil compacted at an initial degree of saturation S_0 = 20 % decreased by 25, 22, and 26 % for soil treated with lime while decreasing by 41, 40, and 43 % for soil treated with silica fume for the three soil respectively, soil A, B, and C. When the soil compacted at its effective degree of saturation S_0 = 50 %, the rate of flow decreased by 43, 41 and 41 % for soil treated with lime while decreasing by 55, 56, and 57 % for soil treated with silica fume for the three soil respectively, soil A, B, and C. Therefore, silica fume is more effective in decreasing the rate of flow than lime.

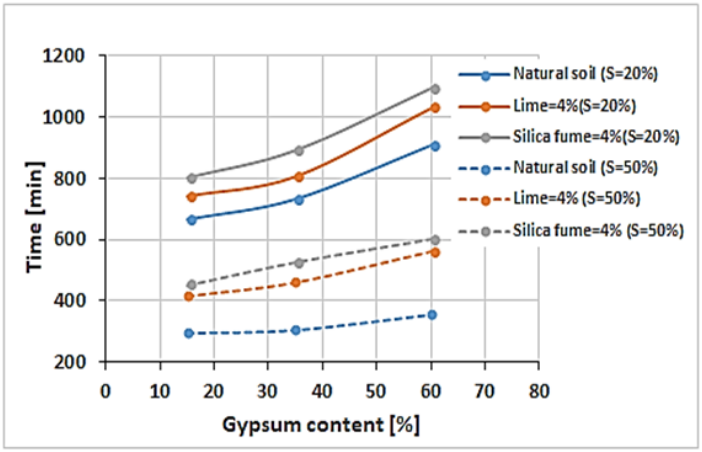


Fig. 11: Variation of entire saturation time with gypsum content for treated and untreated gypseous soil.

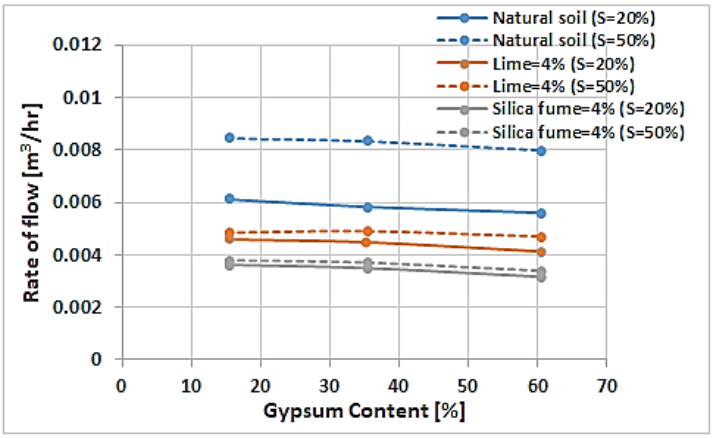


Fig. 12: Variation of rate of flow with gypsum content for treated and untreated gypseous soil.

From the above discussion, it could be seen that the soil compacted at an effective degree of saturation S_0 = 50 % is more effective in increasing the time required for reaching the full saturation stage, and decreasing the rate of flow. This behavior could be attributed increased reaction of lime and silica fume as increasing the initial degree of saturation which resulting more hydration products material that could fill more voids, alter the structure of the soil, and decrease the seepage. In addition, increasing the compacted initial degree of saturation increases c and c' causing increasing shear strength of soil [23]. Therefore, it could be said that soil compacted at a low degree of saturation will have large threaded pores and the behavior of soil is like a grained soil [14].

4 Conclusion

The present study summarized the following conclusion:

1) Air entry value and residual value for untreated gypseous soil increase with increasing gypsum content.

2) SWCC for soil treated with silica fume shifted right horizontally than SWCC for lime and air entry value, a residual value for soil treated with silica fume are greater than for soil treated with lime.

3) The percent of increasing air entry value for soil treated with lime was 100, 133, and 150 %, and residual value increased by 39, 60, and 70 % for the three soil respectively soil A, B, and C.

4) The percent of increasing air entry value for soil treated with silica fume was 150, 200, and 225 %, and residual value increased by 54, 73, and 77 % for the three soil respectively soil A, B, and C.

5) Silica fume is more effective than lime in decreasing the rate of flow and increasing the time required for full entire saturation.

6) Treated soil is more effective in increasing the time required for saturation and decreasing the rate of flow when compacted at an effective degree of saturation S_0 = 50 %.

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