Experimental Investigation of Capillary Rise in Unsaturated Gypseous Soils

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Abstract. Capillary rise is a phenomenon that must be considered an inevitable factor when dealing with unsaturated gypseous soil. This study investigates the behavior of gypseous unsaturated soil under capillary action, where different gypsum content and soil densities are experimentally tested in a developed laboratory model consisting of Transparent pipes 1 m long and 0.05 m in diameter. All the pipes are placed inside a rectangular basin with a dimension of (1500×500×500 mm). The soil was taken from Tikrit city in Iraq at a depth of (1.5 to 2 m) under the natural soil surface; the laboratory tests clarified that the soil is poorly graded sand with a gypsum percent of 59%. The three other gypseous soil samples were prepared by dissolving with HCl acid to gain the required percentages of gypsum (22, 37, and 6%). The results show that the presence of gypsum in the soil slows down the rise of water in the soil after rapid rising in the first stages of the test. The low and moderately gypseous soils required a shorter time to reach the maximum capillary rise than highly gypseous soils. Also, the existence of gypsum increased the max. The height of the capillary rise and the degree of saturation in the capillary zone were also noticed for all soil densities examined. The effective stress will be low in the fully saturated parts while it's high in the low saturated parts.

Keywords: Gypseous soil, unsaturated soil, capillary rise, capillary model, gypsum content.

1. INTRODUCTION

Capillarity is a combination of cohesion force (that causes water particles to stick to one another and form water droplets), adhesion force (which is responsible for the attraction between water and solid particles), and surface tension forces. In soil, the water will rise, supplanting air until the pressure under tension is at equilibrium with the gravitational forces pulling the water downward. The capillary pressure is always negative, gives a suction effect, and increases the effective stress in the soil mass. The capillary rise may affect the foundation and structure materials, even if above the water table, but in touch with the capillary fringe. This will raise the moisture in building materials and lead to mold problems, weakening the building's structure and debilitating the building's foundation [1]. Gypseous soil is considered one of the problematic soils that challenge geotechnical engineering. In Iraq, several cases of cracks and deformations occurred in structures due to the exposition of gypseous soil to water. It was noticed that the dry state of the gypseous soil generates a high bearing capacity and low compressibility. When the gypseous soil is exposed to water, the collapsibility of the soil will be increased. The dissolution of salts inside the soil mass will create new pores inside the soil structure and lose the bonds between the soil particles, leading to the metastable structure [2-6].

In unsaturated soil mechanics, soil suction is considered a combination of matric suction and osmotic suction. The most influential force is the force that comes from the matric suction [7-9]. The matric suction is useful in determining shear strength, permeability, and effective stress [10-11]. Suction provides an additional normal bonding force (stabilizing effects) at the particle contacts, attributed to capillary phenomena occurring in the water menisci or contractile skin [12]. The effects of suction are affected by the degree of saturation of the soil. The relative area over which the water and air pressure performance depends directly on the degree of saturation (the percentage of pore voids filled by water), but the same parameter also influences capillary-induced inter-particle forces [13]. Moreover, the volume change of gypseous soils under suction control tests showed a significant volume change, and the collapse deformation occurred upon matric suction reduction [14].

The capillary in the soil increases saturation, thereby causing consistent changes in stress and strain generated in the soil under the external load. Therefore, the inevitable determination of capillary rise is of great significance to the design of the substructure and channel because the maximum capillary rise height is tightly connected to the strength reduction [15]. The analytical estimation of the maximum capillary rise in the soil is extremely difficult due to a nonuniformity of particle size and the complexity of the packing geometry of soil [16]. The most general empirical Equation estimated by Hazen as shown in Equation (1):

$$h_c(\text{mm}) = \frac{C}{e\,D_{10}} \quad (1)$$

Where C is a constant varying from 10 to 50 mm^2, e is the void ratio, and D_{10} is effective particle size in (mm) [17].

Moreover, [16] arrived at an empirical equation in which the height of capillary rise (in mm) can be defined as a function of the particle size (mm) at the 10% and finer fraction D_{10} as shown in Equation (2):

$$h_c(mm) = -990 \ln D_{10} - 1540 \quad (2)$$

Where h_c= maximum height of capillary rise, D_{10}= effective grain size ranges from 0.006 - 0.2 in (mm), [8].

The Lab. experiments seem to be more accurate than mathematical models. [18] carried out experimental tests on uniform sandy soils. The soils were carefully packed into 50mm diameter glass columns. These columns were placed into transparent plastic tanks with water levels held constant. The results showed that the average height of the capillary rise by equations is smaller than the values measured in the laboratory. The capillary rise of water within the soil column was found to increase as the level of compaction increased [19]; compaction conducted to the soils extracted by Geoprobe from the field resulted in a breakdown in particles, which may lead to blockage of capillary tubes already formed and decreases the volume of water that can be drawn up.

Existing gypsum in the soil causes many engineering of the soil characteristics. Although the investigation of the capillary phenomenon in soil has been going on for more than 100 years, in addition to many studies that have been conducted, much improvement is needed in predicting and calculating capillary rise, especially for problematic soils, i.e., gypseous soils. The equations proposed do not consider all of the essential parameters and use assumptions that may not be accurate. In this study, the capillary rise in gypseous unsaturated soil was investigated by measuring the capillary rise using Laboratory model special tubes. Different densities of gypseous soil and different gypsum percentages were considered. Also, samples were taken from different levels of the capillary tube at various times to measure the water content, the degree of saturation, and the amount of gypsum dissolved due to the capillary action.

2. SOIL PROPERTIES AND EXPERIMENTAL PROCEDURE

2.1 Samples Preparation

The appropriate soil samples were collected from the Tikrit University site in Iraq. The soil samples were extracted from the bottom of the pit (1.5-2.0 m depth) to ensure collecting gypseous soil with the same properties. The gypsum content was found to be 59% based on [20] method. The classification and physical properties of the soil were found according to ASTM [21]. The results are shown in Table 1. This soil can be classified as moderately dense light gray to white poorly graded sand with no fines (SP), and it can be considered very highly gypseous soil. The HCl Acid was chosen as an effective method to prepare soil samples with different gypsum content during a reasonable time and achieve low gypsum percent less than 10% [22]. After several trials, it was found that mixing 5 ml of acid with one liter of water can be effective in dissolving the gypsum in 5000 gm of soil. Started with gypseous soil of 59% gypsum content, and so on to accumulate soil samples with different gypsum content, where high, moderate, and slightly gypseous soils are collected with (37, 22, and 6) % gypsum content, respectively. The physical properties of all soil samples collected are tabulated in Table 1.

Table 1: The properties of the gypseous soil samples.

Properties		Type of soil			
Gypsum content		59%	37%	22%	6%
M.I.T. classification	Gravel	20%	20%	19%	19%
	Sand	78%	77.5%	79.5%	79%
	Fines	2%	2.5%	2.5%	2%
Specific gravity (Gs)		2.51	2.55	2.58	2.62
Atterberg Limits	Liquid limit (L.L) %	26	13	19	22
	Plastic limit (P.L) %	N.P	N.P	N.P	N.P
Maximum Unit weight (kN/m^3)		16.25	16.5	16.7	17.0
Minimum Unit weight (kN/m^3)		15.5	15.7	15.9	16.2
Unified soil classification		SP	SP	SP	SP

2.2 The Experimental Model Setup

The experimental setup consists of the basin and the tubes, as shown in Figure 1. The rectangle basin was made of galvanized steel with inside dimensions (1500 mm× 500 mm×500 mm). At the top surface, three steel holding rings were welded to the basin. A clear reference line was drawn at the side plates of the water basin to advise the water's elevation and constrain the water at the same level during all the periods of the tests. The tube system consists of transparent plastic tubes with an inside diameter of 50 mm and 1000 mm in length. A ball valve made from high-density polyethylene is connected from the top to the plastic pipe; a 50 mm mesh filter is placed above the gate to prevent the soil from escaping when the valve is in the open state. The valve is used to allow the movement of the water through the soil during the capillary action and to control the height of the capillary fringe during the test. The ball valve is connected from the bottom with a base cylinder.

The base cylinder is pure plastic with dimensions the same as the plastic tubes. The cylinder is perforated around the sides with holes of 2 mm in diameter to allow the water to enter the piping system; the base cylinder is closed from the bottom with the base plate. The base plate is made from iron steel with a diameter of 150 mm and a height of 50 mm; at the center, a threaded hole of 50 mm is used to connect the tube system. The main purpose of this Plate is to prevent the piping system from falling during all stages of the tests. Screw threads join all the parts above; a sealant tape is used to prevent any water leakage from the tube system.

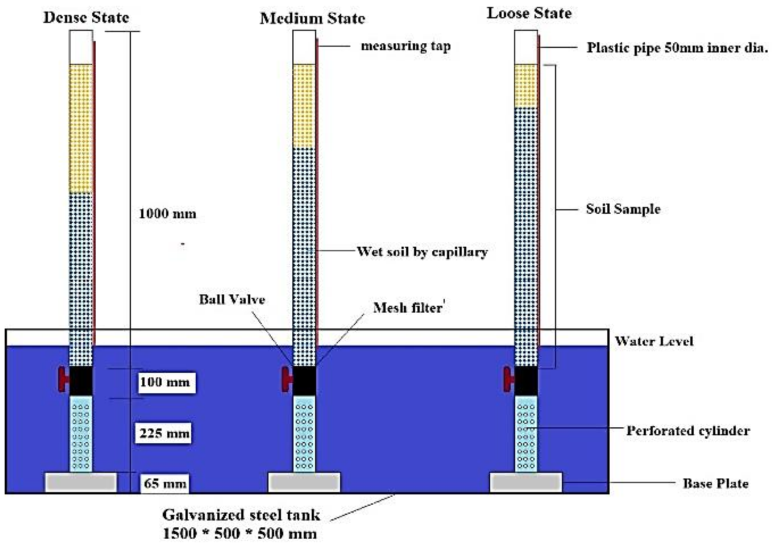

Figure 1: The details of the experimental model setup.

2.3 Experimental Procedure

The experimental work is divided into two series. The first series consists of experiments on the three soil densities for gypseous soil types (very high 59%; highly 37%; moderately 22%; and slightly gypseous soils, 6%). These tests are conducted to understand and evaluate the capillary rise of water in the soil column with time. These tests are continued running until the capillary rise of water becomes almost fixed time. The second series involved evaluating the degree of saturation, water content, and gypsum amount dissolved during different water levels rising with the same four gypsum content in the first series and three densities. These tests are stopped at specified times by using the ball valve. Then, samples are extruded from the soil column by a special tool and tested to find the above parameters.

The amount of soil needed to fill the plastic pipe with 950 mm height is calculated according to soil density and gypsum content that was decided based on the relative densities. The soil samples for all the above tests were sieved on sieve No.4 before getting started with all the tests. Twelve soil samples had been prepared consisting of four types of gypseous soils, (59%, 37%, 22%, and 6%). For each gypseous soil, three density states are chosen: a loose state with an approximate relative density of 30%, medium-density soil with a relative density of 45%, and dense gypseous soil with a relative density of 75%. The soil sample densities were calculated based on the maximum and minimum density results mentioned in Table 1. Each one is filled with compaction by a special rod with a vertical distance of 150 mm. The procedure will continue until the amount of soil is filled to a height of 950 mm. After that, the ball valve is opened to let the water rise through the soil by capillary action, and the time starts to record. The test will continue until the capillary height's steady state is reached and there is no noticeable lift in the capillary. For the second series, the same procedure was repeated as in the first series during the filling of gypseous soil in the plastic tube. Herein, the test will stop by countering the ball valve to the closed position after six hours, then repeated and stopped after 36 hours. The sample will then be extracted; small specimens are tested for gypsum and water content from different levels Figure 2.

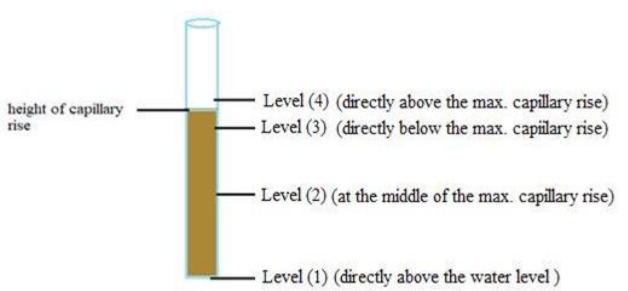

Figure 2: Soil samples taken from different levels of the tubes.

3. CAPILLARY RISE IN UNSATURATED GYPSEOUS SOILS

3.1 Effect of Time on Capillary Rise

Figures 3 to 6 show the relationship between the capillary rise and time for gypseous soil with gypsum content of 6, 22, 37, and 59%, respectively. These relationships are drawn for loose, medium, and dense states. It can be shown from these figures that there is a rapid capillary rise in the first part of the curve, especially in the first four hours of the test after the velocity of capillary rise is reduced, and this continues until the tenth hour of the test. Then, the relationship became steady at a fixed height. For loose soil, the capillary rise for 6% gypsum content is almost the same (0.01 m), while it gives a higher value with gypsum percent of 37 and 59% (0.14 and 0.15 m, respectively).

The capillary rise is between (0.07–0.1 m) for soil with gypsum content of 6 and 22% and medium and dense soil states, while it's more than 0.1 m for soils with gypsum content of 37 and 59%, respectively. This phenomenon transpired due to the rapid capillary rise at the beginning of the test (the velocity is as ordinary as in sandy soils at the beginning of the capillary rise). After that, gypsum losing the bond with other crystals and soil causes a reduction in the capillary rise speed. This is due to the dissolving of small gypsum crystals and absorbing the water, which reduces the capillary rise speed. Also, submerging the soil with water can be considered another reason. For 6 and 22% gypsum percentages, the time needed to reach a maximum height of capillary rise is between (40 – 44 hours) while for gypsum percent 37% and 59%, the steady-state will take a little bit longer time to reach (48 – 60) hours. The main reason is that the rise of water depends on the gypsum's solubility; whenever the gypsum percent is high, the gypsum will take longer to dissolve in water, which means a longer time until reaching maximum capillary rise.

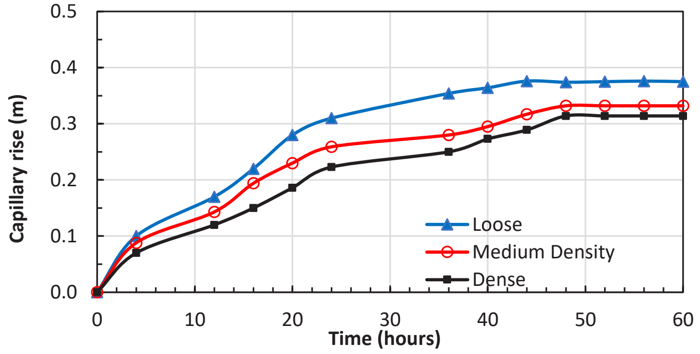

Figure 3: The relationship between height of capillary rise and time for 6% gypsum percent.

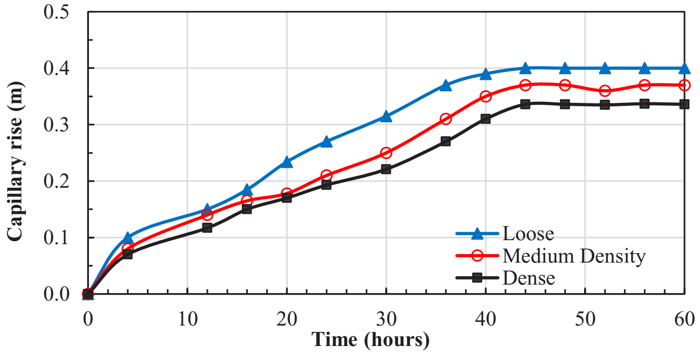

Figure 4: The relationship between height of capillary rise and time for 22% gypsum percent.

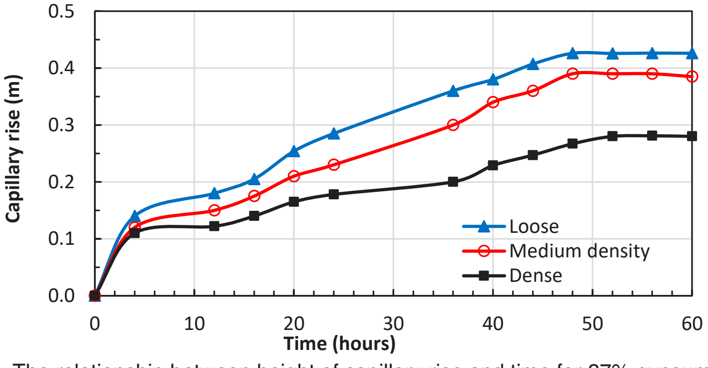

Figure 5: The relationship between height of capillary rise and time for 37% gypsum percent.

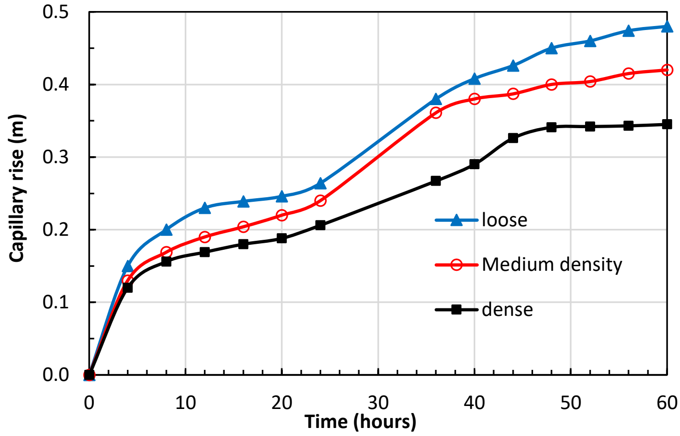

Figure 6: The relationship between height of capillary rise and time for 59%gypsum percent.

3.2 Effect of Density on Capillary Rise

Figure 7 shows the variation of the maximum capillary rise with soil density. It is clearly recognized that increases in density reduce the maximum capillary height. This phenomenon agreed with much recent research despite violating the known Equation of capillary rise in soils. However, the pores among soil particles are found in different shapes and sizes; thus, different arrangements of soil particles, liquids, and gases fill those pores, then the water rises between those pores. The pores are classified as follows: -

- Macro pores: This is effective, and after the source of water stops, the water starts to drain from those pores, and it becomes empty.
- Meso pores: The mesopores start to be effective when the macropores become empty of water.
- Micro pores: This is considered the most important one because the water remains in it and starts to move slowly, which will be influential in the rise of water due to capillary rise [23].

The soil compaction almost closes the macropores and mesopores, and the micropores are the way for the water to rise to the soil tube. The relationships in Figure 7 also indicate that the increase of the gypsum content in the soil leads to more effect of soil density on the reduction of maximum capillary rise, i.e., the gypsum may control the maximum capillary rise. The soil compaction leads to the closing of the pore spaces besides the dissolving. The small crystal of gypsum reduces the path of capillary rise. The effect of soil density can also be discussed by referring to Figure 8; in this figure, the relationship between the relative densities of the soil with the maximum capillarity rise is drawn. The curves in this figure indicate a similar behavior, whereas the relative density increased the maximum capillary decrease. Also, these curves confirm what was discussed in the previous paragraphs about the effect of gypsum percentage and soil density on the maximum capillary height. For all gypsum content in the soil, the density variation seems to be the same. Figure 7 shows that the highest capillary can be obtained when the density is 15.72 kN/m^3, while the minimum capillary rise occurs when the density is 16.79 kN/m^3.

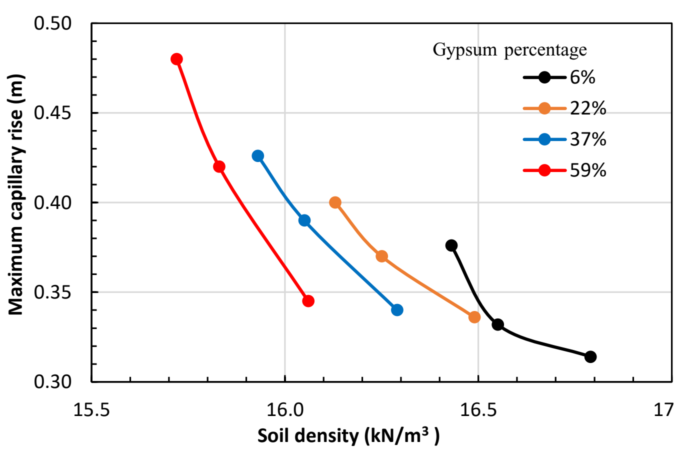

Figure 7: Relationship between soil density and maximum capillary rise for different gypsum content.

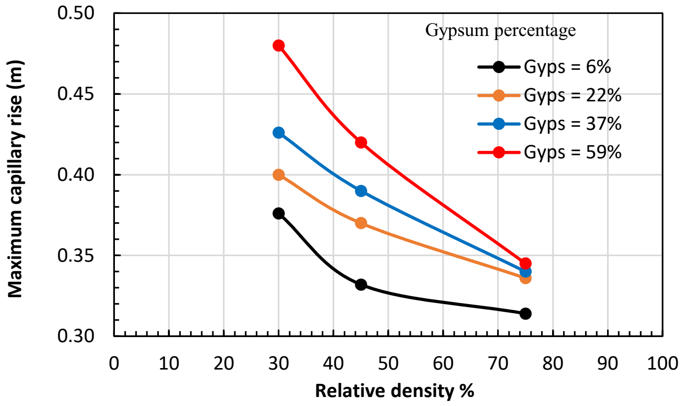

Figure 8: Relationship between relative density and maximum capillary rise for different gypsum content.

3.3 Effect of Gypsum Percent on Capillary Rise

The effect of gypsum content in soil on the maximum capillary rise can be well recognized from Figure 9. It can be shown that the maximum height for soil with a gypsum percent of 59% is 0.48 m for loose soil, 0.42 m for medium, and 0.345 m for dense soil. While for gypsum soil with a gypsum percent of 6 %, the capillary rise is 0.376 for loose soil, 0.332 for medium soil, and 0.314 for dense soil. When the gypsum percent is high, this will lead to a higher capillary rise value because the water will take the gypsum to dissolve as a way to rise by dissolving it, which leads to the difference in the values of capillary rise among the different gypsum percentages. Al-Obaidi and Najim [4] stated that the initial void ratio increases with the increase of gypsum content in the soil until reaching a certain limit where the initial void ratio starts to decrease.

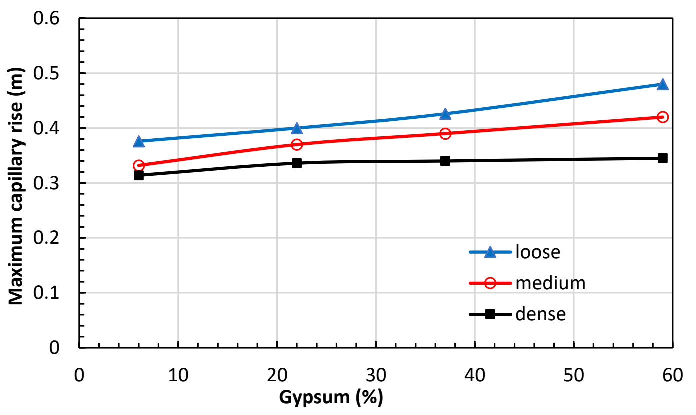

Figure 9: The relationship between gypsum percentage and maximum capillary rises for different soil states.

3.4 Alternation of Gypsum Content and Degree of Saturation with Different Levels of Soil Column

The percentage of gypsum in the soil is measured at different levels for 6 hours and 36 hours from the start of capillary rise, where the effect of water on gypsum starts to be active. The result is shown in Table 2. The results show that when the gypsum percent is high, the obtained operation of gypsum will be high, too. In the first two levels of the soil column, the water will make a path upward the tube by dissolving the gypsum of the soil; when the gypsum percentage starts to decrease, the gypsum will decrease too, as shown for 6% and 22% gypsum content. The degree of saturation along the path of the capillary rise was also calculated from the results of the samples obtained from the levels (1, 2, 3, and 4), respectively. The chosen time to study the behavior of degree of saturation is reasonable to be at 6 hours and 36 hours after capillary start rising, respectively, where the gypsum starts to dissolve after 4 hours of the test. In the late stages of the test (after 44 hours), the capillary rise is almost the same; this will give a point that the degree of saturation is hard to indicate. The best time to study the degree of saturation at the late stages of the test is 36 hours. It can be shown from Table 2 that the process of the saturation of the soil is clear; at the first level, the soil is fully saturated. This is due to the continuous rise of the water over time and the closeness of those levels to the source of water.

The wetting process of the dry soil is similar to the capillary rise. In the first stages, this process is the same as the infiltration process but in the opposite direction (against the direction of gravity) by the time the water continues to rise until it reaches the equilibrium state. The degree of saturation above the maximum capillary height is about 10%, while the percentage of the wet soil is low above the maximum capillary height. At the first level of the tube, the degree of saturation equals 100%, where the soil is fully saturated. Fredlund and Rahardio [7] stated that the zone above the water table is called capillary fringe; the degree of saturation in this area will be 100%. For the intermediate levels, the degree of saturation in the second level (in the middle of the tube) ranged between (60-80%) for the three states of the soil, which is considered an almost high degree of saturation, while it starts to decrease in the upward direction (10-30%). The behavior of the degree of saturation is the same for the three states of soil with a gypsum percent of 6%.

For gypsum percentage, 22%, the first level from the bottom is also fully saturated 100%, while the last level above the maximum capillary height is less than 10% for the three states of soils. The degree of saturation in the second level from the bottom is more than 80% for 6 hours and 36 hours in the three states of the soil, while the degree of saturation in the third level is below the maximum height of capillary height with (0.01 m) ranged from (40-50%). For 37% gypsum percent, the degree of saturation in 0.01 m from the water level is 100% for the three states of soil and for times of 6 hours and 36 hours, as shown in Table 2. For the next level above the first one, it can be noticed that the degree of saturation is also in the fully saturated state for different states of soil in an additional time. This is due to the process of gypsum solubility, which increases the rise of water, reaching this level, so the degree of saturation will be 100% at this level.

For 59%, the degree of saturation is observed in the gypsum, as shown in Table 2. The above figures show that the degree of saturation in the first two levels is the same as the 37% gypsum percent due to the high percentage of gypsum in the soil. It starts to decrease in the third level below the maximum capillary height, ranging between (55-80%), and for the last level, the degree of saturation ranges from (20 to 30%). There is a certain increase in the degree of saturation above the maximum height of capillary rise where the range is more than the other three ranges that were observed in the previous three percentages; this gives a clear indication that whenever the gypsum percent is high, the degree of saturation will be high too. The results agreed with [24], who mentioned that the degree of saturation in the first levels from the bottom of the sample is almost constant (70 – 100%). It starts to decrease rapidly upward until reaching the dried soil above maximum capillary rise, where it’s almost reduced to (zero-10%).

Table 2: The gypsum percent and degree of saturation in soil after capillary rise.

Gyp. %	Levels	Gyp. (%) after capillary rise for two Times		Degree of saturation for two times					
				Dense soil		Medium dense		Loose soil	
		6 hrs.	36 hrs.	6 hrs.	36 hrs.	6 hrs.	36 hrs.	6 hrs.	36 hrs.
59	1	48	47	21.0	22.5	21.87	24.34	30.5	27.5
	2	52	53	73.5	77.05	58.03	72	71.2	74.5
	3	58	58	100	100	100	100	100	100
	4	59	59	100	100	100	100	100	100
37	1	30	28	13.6	14.4	15	14	14.92	15.84
	2	35	35	56.9	65	59	61	46.43	67.0
	3	36	36	100	100	100	100	100	100
	4	37	37	100	100	100	100	100	100
22	1	15	14	7.31	8.1	8.2	7.8	8.4	7.5
	2	20	19	47.6	45.5	39.9	42.6	41.4	42.3
	3	21.9	21	100	100	86	88.1	87.8	88.6
	4	22	22	100	100	100	100	100	100
6	1	4	3.8	4.1	4.5	5	4.8	4.2	4.8
	2	4.9	5	20.1	23.6	23	27	14	11
	3	6	6	68	63	68	65	78.4	77.4
	4	6	6	100	100	100	100	100	100

4. CONCLUSIONS

From the obtained results from the developed model for capillary in unsaturated gypseous soils, the following conclusions can be drawn: -

- The capillary rise will be rapid in the first hours of the test until reaching 10 hours, where the velocity of capillary rise starts to decrease because of the loss in the gypsum bonds with other crystals and soil.
- For low gypsum percent, the time needed to reach the maximum capillary rise is low; on the contrary, for high gypsum percent (more than 35%), the time required to achieve the maximum capillary rise is high.
- The gypsum will become more soluble over time due to capillary rise. Also, increasing gypsum percent in the soil leads to more effect of soil density on the reduction of maximum capillary height so that the capillary rise can be controlled through gypsum percent. When the relative density increases by compaction, the effect of capillary rise decreases, vise-versa, especially with high gypsum percent. The capillary rise will be low in soils with large densities and vice versa in soils with small densities.
- The degree of saturation in the soil will be hard to indicate in the late stages of the test; therefore, it's preferred to study the behavior of the degree of saturation after the first four hours of the test, reaching 36 hours.
- The degree of saturation will be 100% for the levels above the water source, and it starts to decrease upward.
- For high gypsum percent, the degree of saturation will be high, too.

- The effective stress is not easy to predicate in soil without considering the effect of groundwater level. The effective stress will be low in the fully saturated parts and high in the low saturated parts.
- The pipe system is considered an effective way to study the effect of capillary rise in gypsum soil.

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