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Variation of Collapse Potential with Initial Suction Pressure for Natural and Treated Unsaturated Gypseous Soil

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ABSTRACT

An experimental program is used to look at the impact of different parameters on the collapsibility of treated and untreated gypseous soil which is one of the most intricate soils. It is experiencing a high strength when it dry, but when subjected to wetting, it experiences a high collapse and volume change. A single odometer test was utilized to specify the collapsibility of soil. Lime and silica fume were utilized to detract the collapsibility of gypseous soil at a percent from 0 to 8%. The soil compacts at its field dry unit weight. Hence, while applying treatment material to stabilize the soil, it is crucial to specify the beginning ratio of saturation (So) that yields a satisfactory compaction result and optimal connection among soil particles. These factors were examined to determine the effects of varying starting suction amounts and starting saturation ratios on the collapsibility of both treated and untreated gypseous soil. Furthermore, a saturation-effective ratio that achieves the lowest collapse potential would be defined. The filter paper method was utilized to specify the initial matric suction to examine how it affects the soil's ability to collapse. The primary findings indicate that for both natural and treated soils, compacting the soil at a starting saturation ratio of 10, 20, and 30 percent results in a reasonably high collapsibility. Between 40 and 50 percent was the effective saturation ratio that yielded the lowest collapsibility. Soils' collapsibility was seriously affected by suction pressures. The disparity in the matric suction of the compressed specimens during the soaking had less of an influence on the collapsibility of the treated gypseous soil (particularly treated with silica fume) than untreated soil. To imitate the collapsibility of both natural and treated gypseous soil, an empirical equation is expected.

1. INTRODUCTION

Unsaturated soils with a large volume loss upon impregnation, together with or without additional stress, are called collapsible or metastable soils. Collapsible soils typically keep an unlock, "honeycombed" formation with cementing agents that produce significant shear strength and negative pore water pressure [1]. Effective stresses are decreased due to wetting because the negative pore water pressure is dissipated. Additionally, the water dissolves and mitigates the bind that holds the soil particles together, resulting in a denser packing of particles but a reduction in shear strength. Gypseous soils are categorized as collapsible soils. Particles of gypsum seem to function like cement when the soil is tumble-dried, but once water is introduced, the soil dissolves and becomes softer, which could cause the structures to fail partially or completely [2]. In a good deal of geotechnical employment, such as strata under dams, infrastructures, and highways, the establishment of soils is vitally important to avoid geotechnical problems [3]. Stabilization of the soil with additives like silica fume, fly ash, and lime, which are the most popular industrial by-product pozzolans, is used in the soil to improve the soil properties. Aluminous and siliceous elements make up pozzolans, which, when combined with calcium hydroxide in very small quantities and the presence of water, result in cementitious materials [4].

At times, soil compacts to a particular relative density (RD) at its field dry density. As a result, it's critical to identify the starting saturation level that produces the best compaction outcome and particle-to-particle interaction, particularly when treating the soil with treatment material. Finding the impact of initial suction pressure variation on collapse potential is also crucial. This variation arises from variations in the beginning ratio of additive material and saturation.

The idea of an effective saturation ratio and its effect on collapsibility qualities was investigated. Nevertheless, a saturation-effective ratio was defined as follows by Basma and Tuncer [5]: “The beginning ratio of moisture that up above, insignificant collapsibility subsists for a whole anticipated domain of correlative compaction and overburden pressure.” The initial ratio of saturation (So) is the beginning magnitude of moisture that is appended to the soil to compact it, which corresponds to the generation of the beginning suction pressure in the soil.

Lime stabilization is one of the most popular techniques attendant to its economy and suppleness. It is frequently utilized as a stabilizing operator in numerous geotechnical engineering works, including footing bases, layers beneath roads, earth dams, and other structures [6]. Typically, between 1% and 10% of lime is applied, and between 1 and 56 days are required for curing. Bell in 1996 [7] found that the strongest enhancement in strength visible transpired between 4 and 6 percent of lime but the total augmentation in strength was based on the quantity of water applied and the length of curing. Al-Janabi in 1997 [8] found that as lime content increases, the unconfined compressive strength of gypseous soils increases to the highest possible value at optimum lime content. Further increases in lime content cause decreasing in the unconfined compressive strength. This behavior is consequent to the reaction of soil with lime, which produces cementing bonds. Ibrahim et al. [9] verified that lime could be utilized successfully at a percentage of 5% to enhance the properties of gypseous soils, and the soils' collapse potential greatly decreased. Al-Sheakayree [10] studied the shear strength properties of gypseous soil treated with lime and found that lime can successfully improve the soils below the foundations. The treatment percentage is 1.5%.

As a multidisciplinary discipline, silica fume has made great progress. It is obtained from the gases rising from burner funnels during the act of condensation, and it is a byproduct of iron silicate metal synthesis in arc-type burners. The powder is typically gray and looks like fly ashes or Portland cement to some extent. Silica fume-treated soil has a high compression strength, a low coefficient of permeability, durability as well as a high resistance to acids, nitrates, and sulfates [11]. Moayyeri et al. [12] noted that the addition of 1% of lime and silica fume leads to 15 times rise in unconfined compressive strength value as compared with the untreated samples. Al-Obaidi et al. [13] enhanced the collapsibility and shear strength of highly gypseous soils by using silica fume and found that additive material works as an adhesive that leads to improved engineering properties but needs more amount of water for the hydration process. Jassam and Younes [14] studied the effectiveness of adding a combination of silica fume and sand dunes on the properties of gypseous soils and found that the treatment enhances unconfined compressive strength value and a clear reduction in collapsibility. In addition, both the angle of internal friction and cohesion were increased by adding the mixture after 7 days of treatment.

The implications of numerous starting saturation levels and starting suction on the collapsibility of untreated and treated gypseous soil will be examined in this paper. Some studies were conducted in the past to show the effect of many parameters on the collapse of natural soil such as beginning void ratio, beginning water content, beginning density, and wetting pressure This investigation aims to determine how starting suction pressure, which is associated with the starting ratio of saturation (So), affects the collapsibility of treated and natural gypseous soils that have been compacted at field dry unit weight. To replicate the collapsibility of both natural and treated gypseous soil, an empirical equation would also be anticipated and an effective saturation ratio would be stated.

2. EXPERIMENTAL PROGRAM

This study will involve two primary tests: an ASTM D-5333 single odometer test for collapse determination and an ASTM D-5298 filter paper method test for suction determinations. To investigate the impact of starting water content on collapse, all of the specimens were compressed at their dry field weight units to obtain around 78% relative density for different starting ratios of saturation, from 10 to 90 percent. 189 samples in total were tested. Seven samples, each reflecting a different saturation (So) level, were evaluated for each case of natural or treated soil. Each collapse potential (CP) value obtained for this investigation was calculated as the average of the three investigated samples to mitigate the percentage of inaccuracy.

2.1 Soils

Samples of the locally disturbed gypseous soil used in this study were collected from three distinct places in the Salah Al-Dean governorates of Iraq. Soil A, located north of Tikrit city, originates from Baiji city and has a medium gypsum level of 15%. Soil B, located west of Tikrit city, originated from Al-Deoum city and has a medium gypsum content of 35%. Finally, soil C, located north of Tikrit city, originates from Tikrit University and has a high gypsum content of 60%.

Using conventional testing, the physical, chemical, and categorization properties of each soil were identified. The main findings are presented in Table 1. The University of Tikrit's "Soil Mechanics Laboratory" was the site of the soil testing program. Figure 1 displays the grain size distribution curve. By heating the gypseous soil, the hydration method—which is dependent on weight loss—was used to calculate the gypsum content. Gypsum causes the loss of weight [15]. Al-Mufty and Nashat [16] have enhanced this method.

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
Water Content [%]	4.5	4.64	5.57	ASTM D-2216
Liquid Limit (L.L)	28	26	25	ASTM D-4318
Plastic Limit (P.L)	N.P	N.P	N.P	ASTM D-4318
Coefficient of uniformity *Cu*	9.75	3.76	7.46	ASTM D-4254
Coefficient of curvature *Cc*	0.42	0.97	0.69	ASTM D-4254
Maximum dry unit weight (kN/m^2)	17.5	16.7	15.2	ASTM D-698
Minimum dry unit weight (kN/m^2)	12.2	12	11.6	ASTM D-4254
Field dry unit weight (kN/m^2)	16.0	15.4	14.2	ASTM D-1556
Classification according to USCS	SP	SP-SM	SP-SM	ASTM D-2487
Friction angle, φ in (°)	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	46.6	65.2	
pH value	8.05	8.03	7.93	

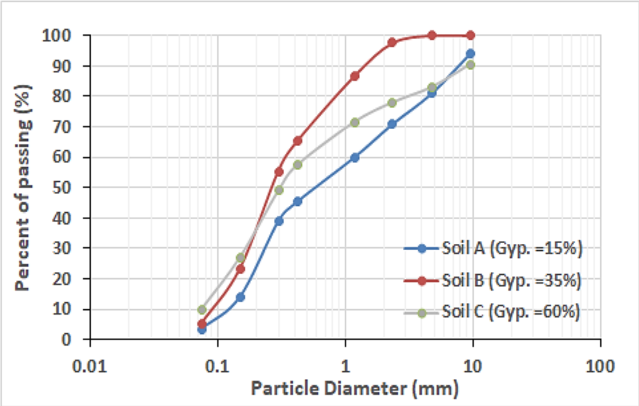

Figure 1. The utilized soils' particle size distribution

2.2 Lime and silica fume

There would be two different kinds of additives used: silica fume and lime. The facility that produced Meshrag Sulphur shipped hydrated lime. Table 2 lists the chemical characteristics of silica fume and hydrated lime. The standard standards of silica fume include all of the major physical features. The silica fume particles are extremely tiny, with over 95% of them being smaller in size than 1 µm.

Table 2. The utilized lime and silica fume's physical and chemical characteristics

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

2.3 Single odometer test

A single odometer collapse test (ASTM D5333, 03) is employed to evaluate the soil collapsibility due to its simplicity. Collapse potential (CP) for each specimen is define as the deformation produced by the addition of water (at the applied stress of 200 kPa) and divided by the original height specimen, expressed in percentage. A comparable quantity of water and additives were manually combined with a predetermined amount of oven-dried dirt. To create a consistent mixture, water is introduced into untreated soil and left inside a tight plastic bag for 24 hours. For treated soil, the mixture is left for an hour to allow for a mellow until compaction takes place [17]. Wet soil was placed inside a 6.3 cm diameter by 1.9 cm high odometer cell ring. The soil was pressed down using modest tampered until the sample's height matched the ring height. In the meantime, ready-made samples were covered with two layers of plastic and permitted to cure at 25°C for seven days.

To ensure a perfect fit amongst the sample and the top cap, an extremely small seating load of 5 kPa was given to the sample ring in the framework of loading prior to the test beginning. After letting settling was established for each loading phase, vertical stress was then applied sequentially. A 200 kPa vertical pressure was applied to the specimen, and it stayed underwater for an entire day. Using Eq. (1), the collapse potential is determined.

$$CP=\frac{\Delta H}{H_o}=\frac{\Delta e}{1+e_o} \quad (1)$$

where, ΔH is the change in sample depth after inundation, H_o is the original depth of the sample, Δe is the change in void ratio due to inundation, and e_o is the initial void ratio.

2.4 Filter paper method

Filter paper technique is employed to assess matric suction in soil using (Whatman No. 42, ashless) filter paper disks. This method is one of the most feasible and simple techniques that can be used to assess an extensive range of suction values (from 0 -100000 kPa) [18]. For this test, two identical specimens measuring 4.8 cm in diameter and 2.5 cm in height were prepared and coated by double nylon for curing for 7 days as shown in Figure 2(a). The samples were prepared employing the same methodology as the odometer test samples. Three filter papers, which are made up of a disk of filter paper seated between two defensive filter papers are then placed between the two identical prepared samples. The samples are quickly foil-wrapped and sealed with plastic binding tape as shown in Figure 2(b). The close connection between the filter paper and the soil facilitates a quick transfer of solutes and liquid-phase water [18]. After many experiments and trials, the untreated specimens are kept in a desiccator for 14 days while treated soil is kept for 20 days because the treated soil requires more time for an equilibrium state. The water content of the filter paper is then calculated by using a balance of (0.0001 g) accuracy and drying by an oven at 110°C as shown in Figure 2(c) and (d). Using the proper curve for calibrating filter paper, the soil matric suction is then computed [19].

(a) Two identical samples (b) Samples of soil

(c) A balance with an accuracy of (0.0001 g) (d) Calculating filter paper water content

Figure 2. Filter paper method

3. RESULTS AND DISCUSSION

The collapse potential (CP), filter paper determination program on soils is divided into three groups. The first group was conducted on natural gypsum soil with different gypsum content of 15, 35, and 60%. The second group was conducted on lime-treated soil, and the last group was conducted on silica fume-treated soils, the results are presented as follows.

3.1 Collapse potential of natural soils

3.1.1 Effect of initial degree of saturation (S_o)

For the three natural soils, Figure 3 illustrates how the collapse potential varies with the starting saturation ratio. It was evident that when the starting ratio of saturation (S_o) was raised, the collapse potential drastically decreased. Another way to make soil more prone to collapsing is to increase its saturation level. This will improve compaction and reduce the chance of collapse. This behavior is explained by the fact that when the soil was compacted with higher initial water content in the past, the first link formed by the fine-grade proportions in the soil was broken, resulting in a reduction in collapsibility. Furthermore, a higher starting water level drastically decreases the meta-stable actions, letting less water drop after soaking. Low starting saturation levels, however, are inadequate to dissolve every gypsum link between soil pieces. Therefore, a lot of water and effort were necessary to change the soil's structure and reduce binding ties [20].

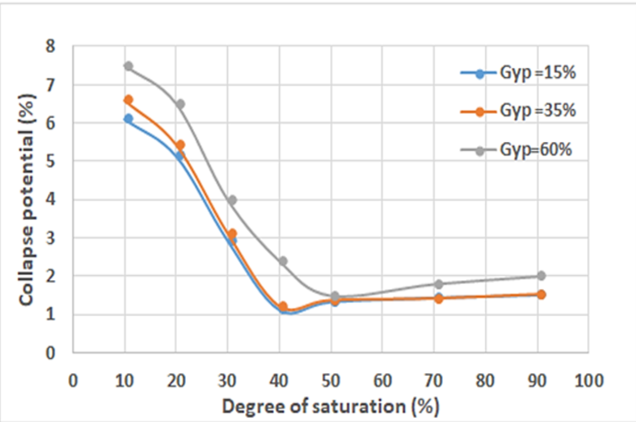

Figure 3. The variance of CP with the beginning saturation level for natural soils

The three gypseous soils had a saturation-effective ratio ranging from 40 to 50% (the soil with a 60% gypsum content had an effective saturation level of 50% due to the substantial specific surface area of gypsum), which indicates that it must retain more water than soil particles. A small rise in collapse potential could be recognized with an additional rise in the starting saturation following a saturation-effective ratio. A plausible reason for this specific occurrence could be that a high moisture content lubricates the particles more and softens their forces, decreasing strength and increasing compressibility [21]. Shear strength of soil improves as a compacted initial ratio of saturation is increased up to 60%, according to Abood et al. [22]. At 80 to 100% degree of saturation, soil shear strength starts to decline. For Soils A, B, and C, the corresponding percentage of decreasing collapse potential at a saturation-effective ratio upon compacting was 78, 77.5, and 76%.

Furthermore, a little increase in the collapse potential value is caused by the aggregate of particles with increasing the saturation level above 40 and 50%, which increases the volume of voids.

3.1.2 Effect of initial suction value

For the three soils, Figure 4 illustrates how the collapse potential varies with the initial suction pressure value. It was evident that as the soil's suction pressure increased, as well the collapse potential. After reaching a minimum collapse value, the collapse potential falls with decreasing suction pressure before gradually increasing. Higher matric suction specimens (above 40–50 kPa) had a higher collapse rate because soil interparticle interaction retains the soil's meta-structure intact. Suction and the connections between them are lost at saturation. Salts, like calcium carbonate, can link particles together. But as the particles get wet from being overloaded, this connection will finally break [23]. Weaker connections would be created between soil particles when the matric suction dropped below the value that reached minimal collapse potential, making the soil microstructure unstable and limiting soil compression.

Furthermore, it was observed that the collapse potential increased as the gypsum concentration increased. According to AL-Omary et al. [24], the suction value rises with increasing gypsum concentration because dissolved salts are present, increasing the soil's tendency for collapse.

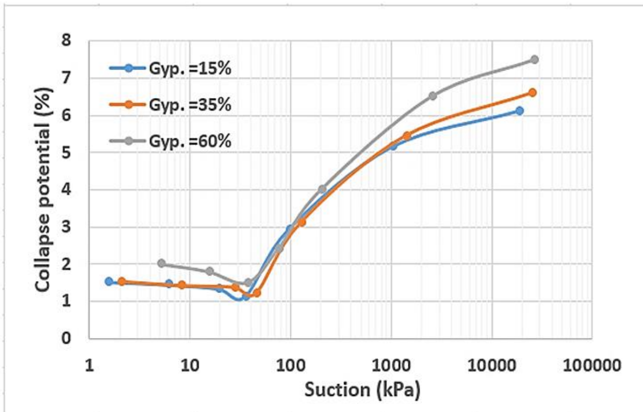

Figure 4. Variation of collapse potential with initial suction pressure for natural soils

3.2 Collapse potential for treated soil

3.2.1 Effect of initial degree of saturation (S_o)

Figures 5-7 depict the disparity in collapse for soil treated with lime, and Figures 8-10 depict the disparity in collapse for soil treated with silica fume at a starting saturation ratio. As the starting ratio of saturation increases, it can be observed that the collapsibility of treated soil diminishes. Even yet, raising the starting saturation ratio caused a greater reactivity of lime in the soil that had been treated with lime. When enough lime and water are used, a soil's pH rapidly climbs to more than 10.5, which supports the breakdown of small-sized soil fragments. Due to the reaction of soils with lime, cementation products would be generated that enhance the stability of soils treated by lime. Furthermore, the cementation compounds formed during lime-soil reactions have rough outer surfaces and high stiffness, which increase the connection and fastening forces among soil fragments [25].

When silica fume was applied to soil, the fumes engulfed the surrounding soil particles and occupied the spaces in the soil sample. A fairly thick layer of silica fume material covered every grain in the soil that had reached the right concentration of silica fume, creating cementing media. Because of this, the aforementioned methods have also eliminated the chance of a chemical interaction between soil particles and silica fume developing. Calcium compounds, found in gypsum soil, combine with water atoms to form Ca^{2+} ions. The interaction of the active silica with calcium hydroxide yields calcium silicate hydrate gels ($CaSiO_3.H_2O$). The effect appeared to make the product less flexible and more durable [26].

Likewise, the three treated soils with lime and silica fume revealed a saturation-effective ratio of 50%, which reached the lowest collapsibility and above it, non-considerable collapse potential. Because more water is needed to conclude the soil reaction with lime to form pozzolanic material, increasing the lime and silica fume concentration by 4% results in an increase in the saturation-effective ratio to 70%.

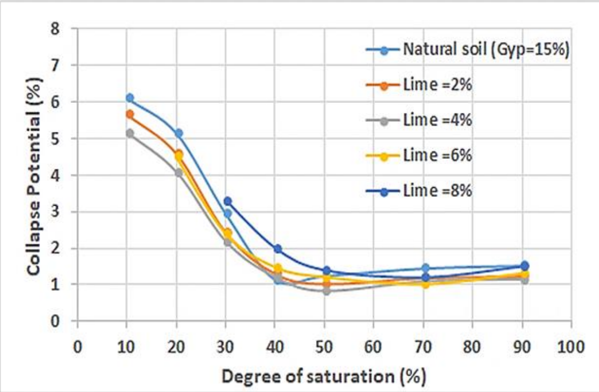

Figure 5. The variance of CP with the beginning saturation level in both natural and lime-treated soils (Gyp.=15%)

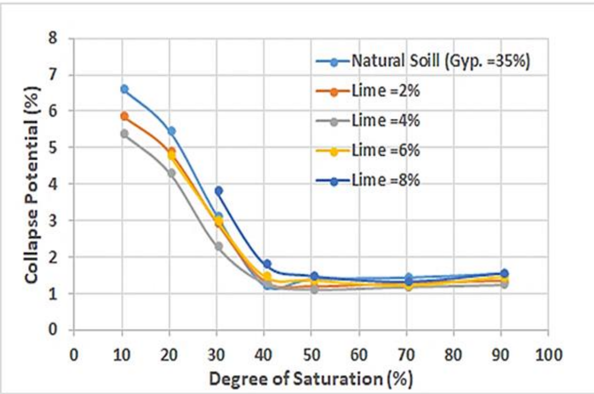

Figure 6. The variance of CP with the beginning saturation level in both natural and lime-treated soils (Gyp.=35%)

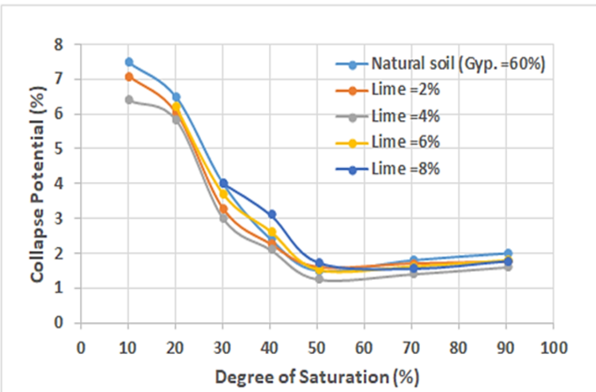

Figure 7. The variance of CP with the initial saturation level in both natural and lime-treated soils (Gyp.=60%)

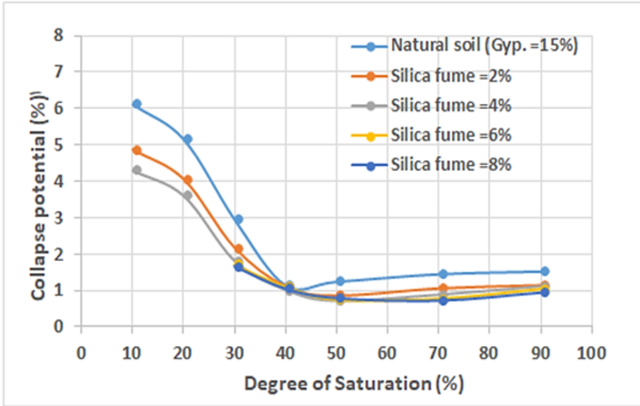

Figure 8. The variance of CP with the beginning saturation level in both natural and silica fume-treated soils (Gyp.=15%)

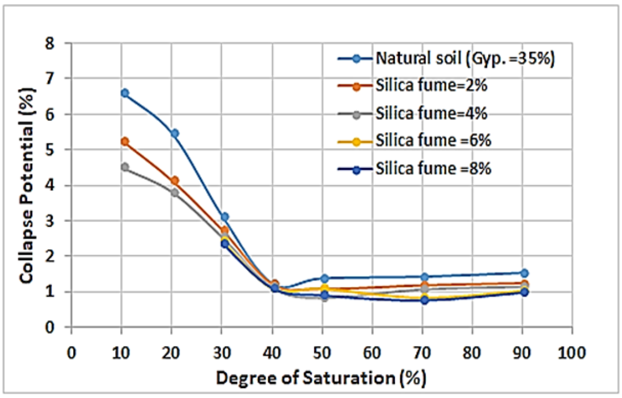

Figure 9. The variance of CP with the beginning saturation level in both natural and silica fume-treated soils (Gyp.=35%)

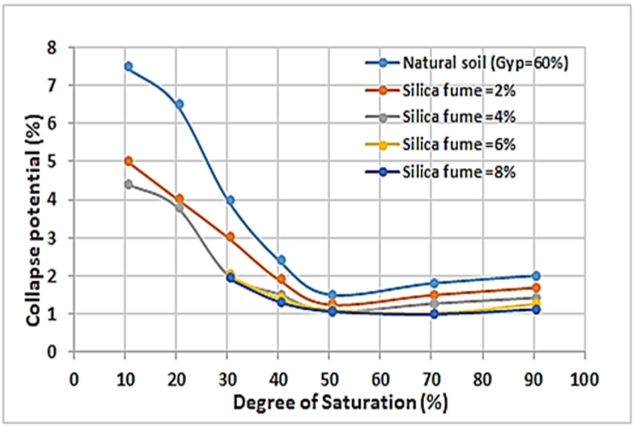

Figure 10. The variance of CP with the beginning saturation level in both natural and silica fume-treated soils (Gyp.=60%)

Stated differently, at low saturation levels during soil compaction (10, 20, and 30%), the behavior of the soil treated with lime and silica fume is comparable to that of granular soil with a broad interconnecting pore (without functioning as a binding agent The hydration products and soil response with additives cause many pores to close at greater saturation levels during soil compaction, increasing the soil's capacity to maintain water. Around the 50% optimal saturation level is where the blocked pore space and open pore state meet [27].

Figures 11 and 12 illustrate how the percentage of additives affects the collapse of soil treated with lime and silica fume that has been compacted to 50% saturation. Lime utilization in the soil revealed that 4% of the lime applied had the minimum potential for collapse. For soil treated with lime, there may be an evident rise in collapse potential as the lime level rises above 4%. An overabundance of lime acts as a lubricant for the soil particles, diminishing their strength because of its low friction and cohesiveness [7]. It was observed that 4% of the addition provided the smallest collapse potential for soil treated with silica fume. Due to silica fume's larger surface area than lime, a minor to negligible increase in collapse probability may be seen as the content of silica fume rises above 4%.

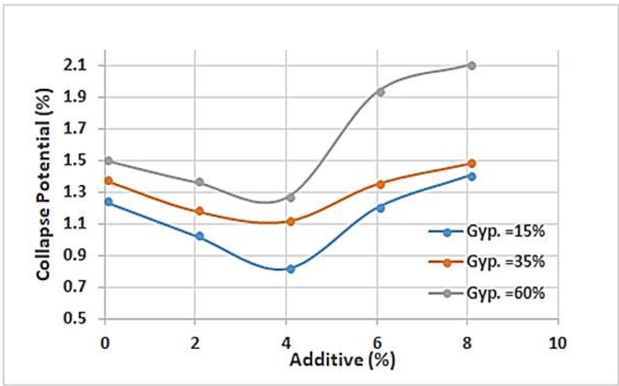

Figure 11. Variation of collapse potential with lime content (S_o=50%)

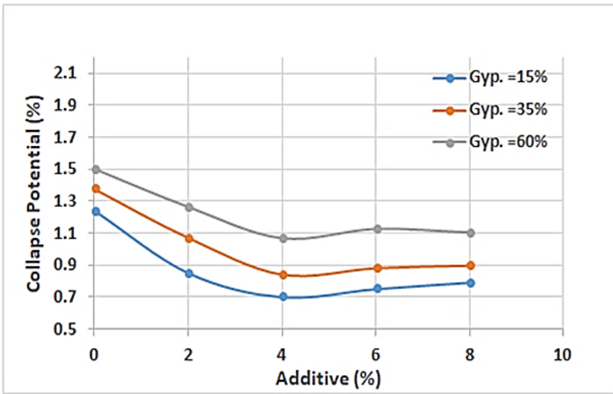

Figure 12. Variation of collapse potential with silica fume content (S_o=50%)

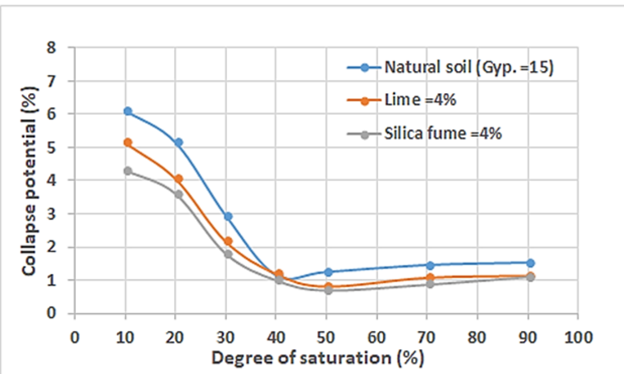

Figure 13. Variation of collapse potential with initial degree of saturation for natural and treated soils (Gyp.=15%)

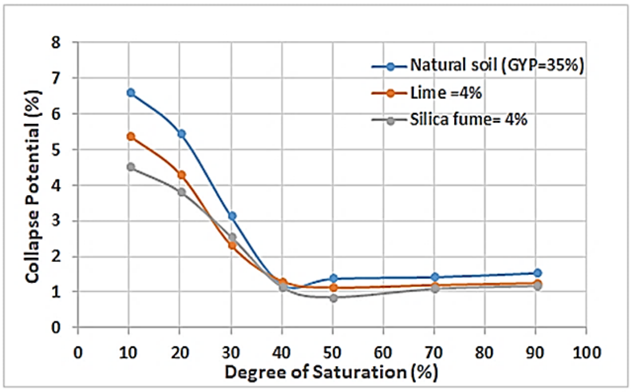

Figure 14. Variation of collapse potential with initial degree of saturation for natural and treated soils (Gyp.=35%)

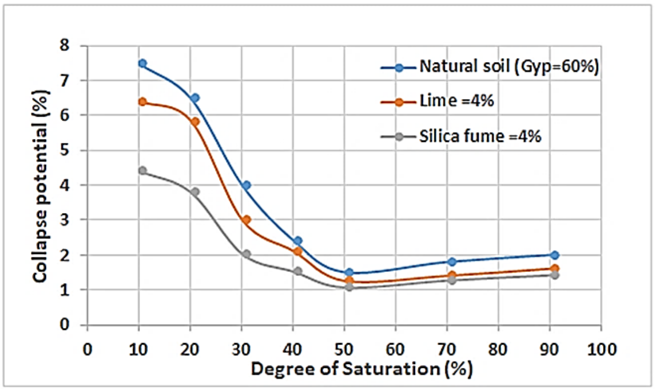

Figure 15. Variation of collapse potential with initial degree of saturation for natural and treated soils (Gyp.=60%)

Figures 13-15 show collapse potential variation with initial saturation level for both natural and treated soils It is evident that silica fume works better than lime, which considerably lowers soil collapse potential when compacted to a saturation-effective ratio of 50%. Reduced collapse percentages for soil treated with silica fume were 86, 84, and 83.6% for soils A, B, and C; equivalent percentages for soil treated with lime and compacted to a saturation-effective ratio of 50% were 84, 80, and 79%. This action results from the silica fume's increased surface area, which may fill in the spaces in the soil sample and wrap the nearby soil particles. As a result, a rather thick layer of silica fume material covered every grain, closing more voids and reducing collapsibility.

3.2.2 Effect of initial suction pressure

The variance in collapse potential (CP) with starting soil suction pressure is shown in Figures 16-18 for the gypseous soil treated with lime; for the gypseous soil treated with silica fume, Figures 19-21 illustrate the variance of collapse potential with beginning suction pressure. It was noted that the collapse potential increased with an increase in the initial suction value, just like in the case of untreated soil. This action may be explained by the high suction value, which is connected to the strong capillary tension that the soil has acquired. Suction pressure exceeding 100 kPa for soil treated with lime and 200 kPa for soil treated with silica fume was identified from the figures to assist in maintaining the soil's meta-architecture utilizing inter-particle connection [28]. These linkages abruptly break down resulting in a loss of suction, which causes soil to generate a noticeably collapsed potential during flooding.

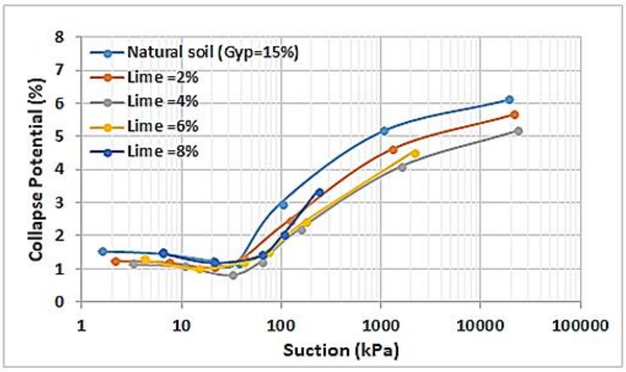

Figure 16. The variance of CP with beginning suction for untreated and lime-treated soil (Gyp.=15%)

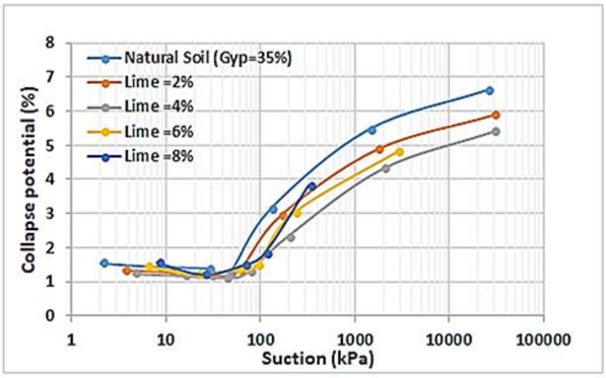

Figure 17. The variance of CP with beginning suction for untreated and lime-treated soil (Gyp.=35%)

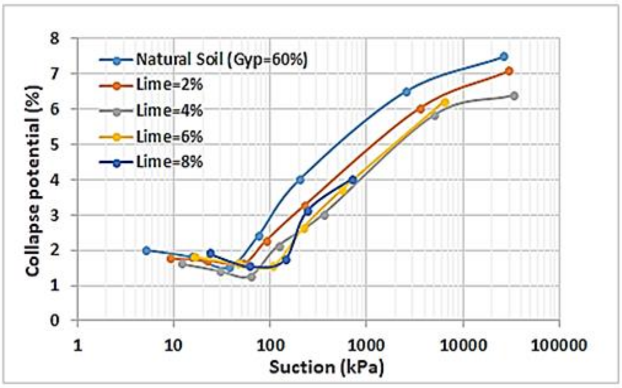

Figure 18. The variance of CP with beginning suction for untreated and lime-treated soil (Gyp.=60%)

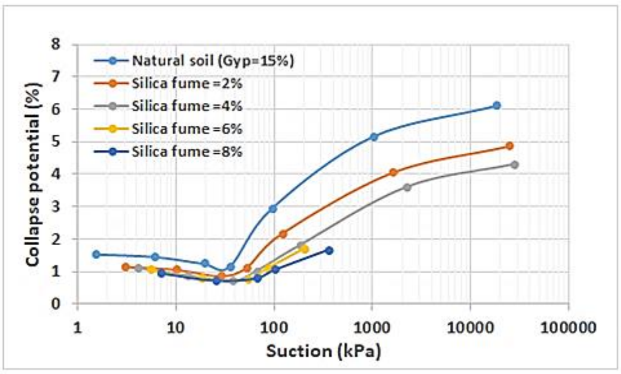

Figure 19. The variance of CP with beginning suction for untreated and silica fume-treated soil (Gyp.=15%)

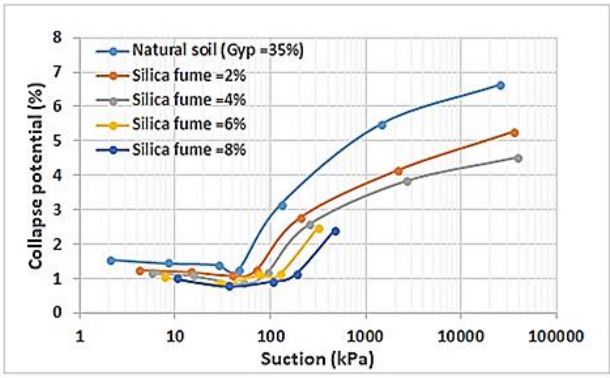

Figure 20. The variance of CP with beginning suction for untreated and silica fume-treated soil (Gyp.=35%)

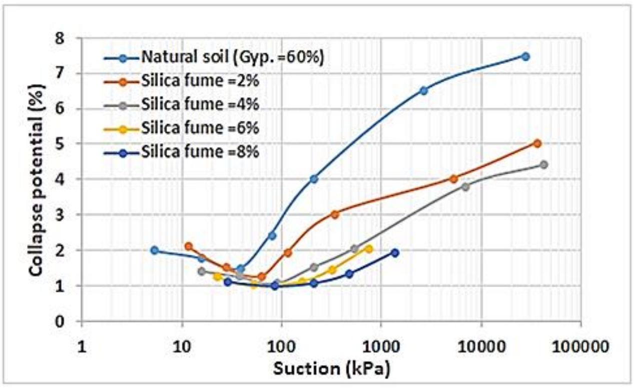

Figure 21. The variance of CP with beginning suction for untreated and silica fume-treated soil (Gyp.=60%)

Reduction of the beginning suction pressure by increasing the beginning saturation level caused a reduction in collapse potential. In situations when the suction value drops more slowly than the suction value that results in the least amount of collapse potential throughout the soil, there may be a modest rise in collapse potential due to the decline in soil structural stability with lowering suction pressure.

The collapse potential changes with beginning suction value for both untreated and treated gypseous soil containing 4% lime and silica fume are depicted in Figures 22-24. The soil treated with lime and silica fume showed a lower collapse potential than the untreated soil, despite being able to withstand a greater suction value at the same starting of saturation level (S_o). To put it another way, compared to untreated soil, treated gypseous soil—especially soil treated with silica fume—was less susceptible to alterations in the matric suction of compacted soil samples throughout the soaking process. Suction pressure in soil therefore exhibits two primary behaviors:

1. Soluble salts and gypsum concentration caused a rise in suction pressure, which raises the possibility of collapse, particularly when compacted at an insufficient beginning saturation level.

2. Because hydration products can fill up the hole in the soil and enhance its matrix structure when pressed to a saturation-effective ratio, the increase in suction pressure brought about by soil stabilization reduces the likelihood of collapse. Even when compacted at low saturation levels, the additional material can certainly decrease void volume, encapsulate soil particles, and enhance soil collapsibility at a simple rate (less than an effective saturation level). However, for a wide range

of suction pressure values, the suction pressure remains the primary factor responsible for soil collapse potential.

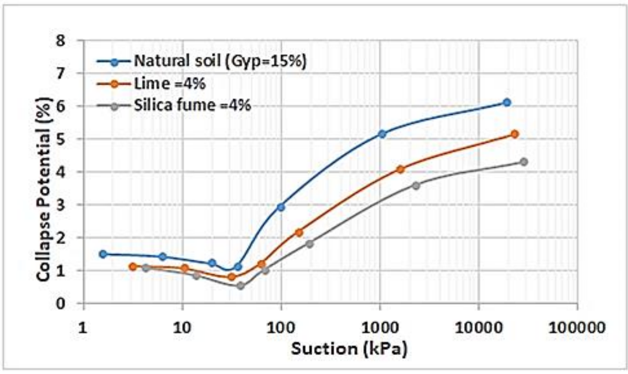

Figure 22. Variation of collapse potential with initial suction for natural and treated soils (Gyp.=15%)

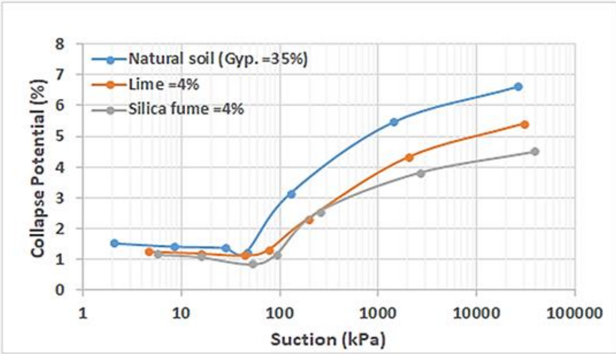

Figure 23. Variation of collapse potential with initial suction for natural and treated soils (Gyp.=35%)

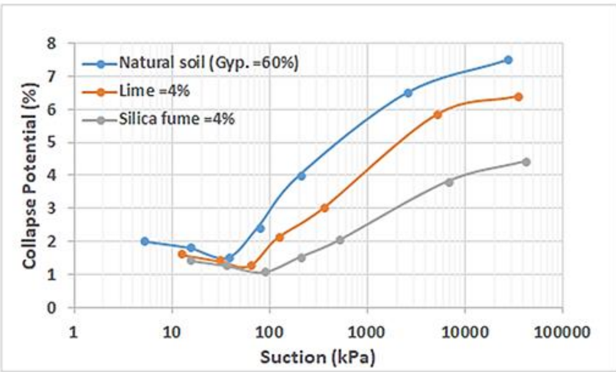

Figure 24. Variation of collapse potential with initial suction for natural and treated soils (Gyp.=60%)

The previous inquiry makes clear that the relationship between collapse potential and the starting suction value or saturation ratio was the same for both treated and untreated gypseous soil. The following three major zones could be used to split it:

1. Low starting water content, high suction, and high capillary force, which arise in soil structure, are associated with the first zone, which has starting saturation levels of 10, 20, and 30%. Pozzolanic material was produced due to an incomplete hydration process of treated material, which was induced by the low initial saturation level. Consequently, a significant portion of included components function as fillers with no interaction or reacting with soil particles, which results in a comparatively high collapse potential.
2. A high saturation level, low suction pressure, and low capillary force created in the soil structure are associated with the second zone, which has a starting saturation level between 40 and 50%. A completed lime hydration process that creates a pozzolanic substance and seals more voids via the treated soil structure is caused by the high beginning water content. As a result, low to moderate collapse potential would occur when soil is flooded.
3. Because the beginning saturation level in the third zone is more than 50%, an effective value is exceeded, leading to a straightforward increase in collapse potential. However, weaker links would form between soil particles as a result of an extreme drop in suction, making the soil microstructure unstable and preventing any noticeable soil compression. Additionally, a little rise in collapse potential would result from some voids created by the conglomeration of soil particles through soil structure.

4. COLLAPSE POTENTIAL CORRELATION

The primary objective seems to be the development of modeling systems that could, in part, given the complex behavior of collapsible soils and the multiple variables influencing it. The moistening outcome must be considered in the framework of the base due to the substantial impact of soil moistening on the collapse and behavior of gypseous soil. To reduce the requirement of performing collapse tests, both in the lab and on-site, some simple correlations to evaluate the variation in the fundamental soil parameters of gypseous soils due to wetting could be beneficial.

In the past, some correlations were attempted to produce the collapse of sandy and silty soil (not gypseous soil) such as [1, 5] with coefficient of correlation (R^2) of 0.82 for both, which considered as a higher coefficient of correlation (R^2) value. They studied the effect of initial water content, wetting pressure, and initial void ratio. It did not take the effect of matric suction on collapse potential.

In this research, IBM SPSS Statistic 22 is used to create new equations for predicting the collapse potential in natural and treated unsaturated gypseous soil. The collapse potential test results from variation in matric suction, initial water content, density, gypsum content, coefficient of uniformity and percent of additive are analyzed. Therefore, two types of equation would be attempted, one for natural soil and the other for treated soil which are they as follow.

4.1 Modified collapse potential equation for the natural soil

A multiple regression analysis was carried out using the experimental data produced by the collapse tests. The derived best-fit equation (Eq. (3)) was with a coefficient of determination R^2 equal to 0.886 is:

$$CP=0.015Gyp. - 0.013\gamma d + 0.046\ Cu - 0.034\ wi + + (Ua - Uw)^{0.188} \quad (2)$$

CP is the collapse potential in percent, Gyp. is the gypsum content in percent, Cu is the coefficient of uniformity of the soil, wi is the initial water content in percent, γd is the compaction dry unit weight in kN/m^3, and $(U_a - U_w)$ is matric pressure in kN/m^2.

From the above equation, matric suction has a more significant effect on the collapse potential of natural soil than the other factors. Therefore, another equation was predicted (Eq. (4)) contained only the effect of matric suction on the collapsibility of soil with a coefficient of determination R^2 equal to 0.868:

$$CP=0.181 + (U_a - U_w)^{0.196} \quad (3)$$

4.2 Modified collapse potential equation for the treated soil

Several models would be attempted to get the optimum simulation for the collapse potential equation for treated soil passed on several variables such as gypsum content, dry density, lime or silica fume content, initial water content, and initial matric suction.

The equation for soil treated with lime with a value of R^2 equal to 0.884 is:

$$CP=0.009\,Gyp. - 0.001\,(Lime\,\%) - 0.019\,\gamma d - 0.016\,wi + (U_a - U_w)^{0.184} \quad (4)$$

With an R^2 of 0.854, the subsequent equation describes soil that has been treated with silica fume:

$$CP=0.007Gyp. - 0.21\,(Silica\,\%) + 0.009\,\gamma_d + 0.011\,wi + (U_a - U_w)^{0.171} \quad (5)$$

Based on the above equation, the matric suction pressure is the most significant variable affecting CP. Therefore, another equation would be predicted to give a good simulation for collapse potential, considering the effect of matric suction pressure only.

With an R^2 value of 0.872, the subsequent equation describes soil that has been treated with lime:

$$CP=- 0.251 + (U_a - U_w)^{0.189} \quad (6)$$

With an R^2 value of 0.767, the subsequent equation applies to soil that has been exposed to silica fume:

$$CP=- 0.503 + (U_a - U_w)^{0.172} \quad (7)$$

The disparity between the expected values from the suggested model and the actual values from the experimental data is depicted in Figures 25-27.

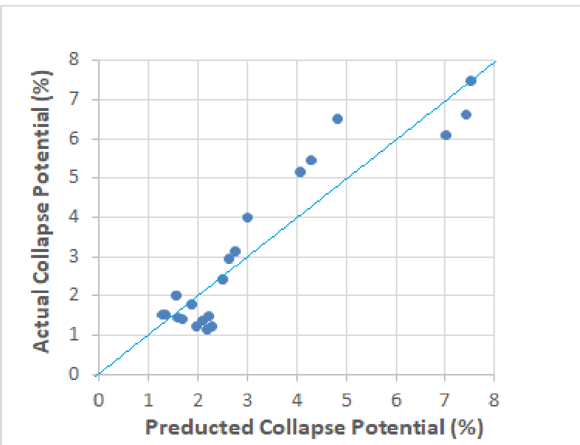

Figure 25. Predicted vs. actual collapse potential values for natural soils

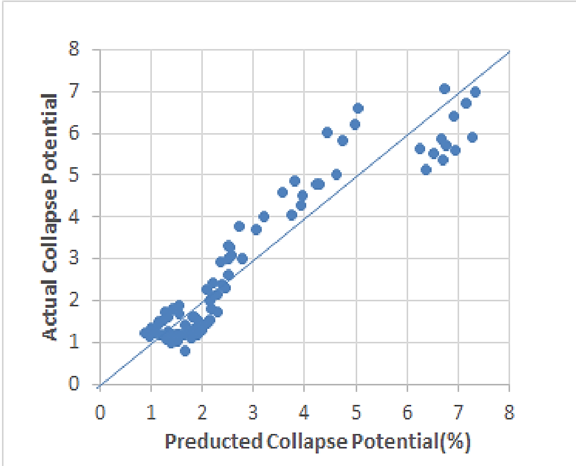

Figure 26. Predicted vs. actual collapse potential values for lime-treated soils

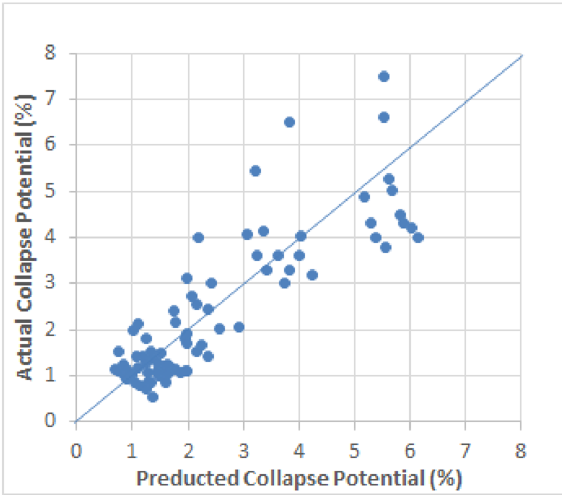

Figure 27. Predicted vs. actual collapse potential values for silica fume-treated soils

5. CONCLUSIONS

The main results show that:

1. The collapse potential of gypseous soil is clearly reduced when lime and silica fume are applied to it, especially when it is compacted a saturation-effective ratio, and this greatly reduces the collapsibility risks from construction on these types of soils that is widely spread in Iraq, such as collapses and cracks that occur frequently in many buildings.
2. Compacted the soils at a low beginning saturation level from 10 to 30 percent leading to a comparatively high collapsibility in untreated and treated gypseous soil.
3. A saturation-effective ratio occurs between 40 and 50% for untreated and treated gypseous soil. Increasing the beginning saturation level above 50% leads to a simple increase in collapsibility as a result of increasing the beginning ratio of saturation above the functional value.
4. In treated gypseous soils, silica fume is more functional than lime. When soil is compacted to a saturation-effective ratio of (50%), it diminishes the chance for soil collapse significantly as follow:
5. For the soil, after lime treatment and compacted to a

saturation-effective ratio showed a declining collapsibility percentage of 84.3, 80.5, and 79.3% for soil, (A, B, and C).
6. For the soil, after silica fume treatment and compacted to a saturation-effective ratio showed a declining collapsibility percentage of 87.2, 85.3, and 83.6% for soil, (A, B, and C) respectively.
7. Moreover, differences in the matric suction of the compacted specimens during the soaking procedure resulted in a lower collapse potential for the treated gypseous soil—particularly the one treated with silica fume—than the untreated soil. This behavior could be explained by the silica fume's large surface area, which blocks new voids through the soil framework and fills up empty spaces between soil particles in soil samples, hence reducing the number of voids and collapsibility.
8. Using a factor of measurement (R^2) ranging from (0.884-0.767), an empirical formula was anticipated for modeling the collapsibility of natural and treated gypseous soil. The results demonstrated that the matric suction is the most crucial variable in the collapsibility of natural and treated gypseous soil.
9. To develop novel formulas for simulating the Mohr-Coulomb failure in unsaturated gypseous soil, both naturally occurring and treated, further investigation is needed in the future to determine the impact of matric suction fluctuation on the shear strength parameter (c and φ).

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NOMENCLATURE

$(U_a - U_w)$	Matric pressure in kN/m^{-2}
CP	Collapse potential in percent
S_o	The initial degree of saturation in percent
C_u	Coefficient of uniformity
w_i	Initial water content in percent
R_D	Relative density in percent

Greek symbols

γ_d	Dry unit weight in $kN.m^{-3}$