Effect of Relative Compaction on Water Absorption and Gypsum Dissolution in Gypsum-Rich Clayey CBR Samples

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Abstract

A clayey gypsiferous soil of CL group according to the Unified Soil Classification System was studied for the effect of relative compaction on water absorption and gypsum dissolution during long-term soaking. The soil has a gypsum content of about 33%. Two sets of soil samples were prepared at optimum moisture content of 11.75% of the modified Proctor compaction test. The first set received 100%, while the second received about 93.5% relative compaction with respect to modified Proctor. These samples were soaked for 4, 7, 15, 30, and 120 days under 40 lbs (178 N) surcharge load. The moisture content was determined at top, quarter points, midpoint, and bottom of each soil sample. The test results revealed that for each compaction effort, the moisture content along each soaked soil sample is not uniform and increased with increasing soaking period. This increase in moisture content is greater for soil samples compacted at the lower compaction effort. The moisture content at top of each soil sample is greater than at the bottom, and the least moisture content took place at the middle of the sample. The dissolution of gypsum, at the top of soil samples, was greater than that at the middle. A multiple regression equation was developed relating strongly the decrease in gypsum content along the clayey CBR samples, with compaction effort and increase in average moisture content along the samples due to soaking. Similarly, strong correlation was obtained from the multiple regression developed between absorbed water, soaking period, and compaction effort. The paper shows that the water absorption and gypsum dissolution decrease with increasing relative compaction as the soil becomes denser.

Keywords CBR samples · Compaction effort · Gypsum · Moisture · Soaking · Soluble salts

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1 Introduction

Gypsiferous soils are found in arid lands such as the Middle East, North Africa, southern central Australia, former inland lakes in Western States of the USA, and also in Europe especially in Spain and former USSR (Van Alphen and Romero, 1971; Hunter, 1988; Kota et al., 2007; Salih, 2013; Bao and Zhang, 2016). Verheyen and Boyadgiev (1997) reported that, worldwide, gypsiferous soils cover approximately 100 million ha.

The presence of gypsum in soils affects most of their properties, causing several physical and chemical problems (Hunter, 1988; Mashali 1996; Razouki and El-Janabi, 1999; Razouki and Kuttah, 2004a, b; Herris et al. 2005; Razouki et al., 2012a; Najah et al. 2013a and Razouki and Kuttah 2019). This is especially important in soils from semi-arid and arid areas, where gypsum behaves as a semi-soluble soil constituent (FAO, 1990).

Gypsiferous soils are not widely used as construction materials due to their unreliable behavior when water exists. Previous studies on these soils showed that dissolution problems in embankments and slopes were associated with gypsum, which may cause a shear strength reduction (Razouki and El-Janabi, 1999; Day, 2000; Razouki and Kuttah, 2004a & 2007; Solis et al., 2008 and Zhao et al., 2017). However, in regions of hot dry climate where water for compaction is very expensive, the use of gypsiferous soil for embankments in hot desert areas becomes logical and economical as discussed by Razouki et al. (2008). The problem of improving gypsum-rich soils by increasing the compaction effort has received attention by Kuttah (2004), Razouki and Ibrahim (2007 and 2019), Razouki et al. (2012b), and Najah et al. (2013b).

Water absorption and associated leaching of gypsum accumulation in the field can be attributed to rainwater, irrigation water, and the rise of water table. According to Ismael and Mollah (1998), tap water is more convenient to use in leaching of gypsiferous soil samples, and it is similar to groundwater in the field.

It is worth mentioning that the problem of water absorption is not only of interest in connection with gypsum-rich soils but even with lime treated soils. Chakraborty and Nair (2020) reported that although lime treatment improves the strength properties of clay-rich subgrade soils, the intrusion of external water can deter the benefits of stabilization processes. Li et al. (2017) studied the effect of environmental conditions on compacted soil behavior in earthworks. In terms of water transfer, they reported that hydraulic loading enhances water exchange with the environment, whereas mechanical loading compresses the volume of voids under nearly constant water content conditions.

However, the effect of long-term soaking on the dissolution of gypsum in gypsiferous soils has received attention by Razouki and El-Janabi (1999) and Razouki and Kuttah (2004b) but unfortunately limited to a certain compaction effort only. Thus, the important effect of relative compaction requires investigation.

2 Relative Compaction

The state of compaction of the soil in the field (or in the laboratory) is expressed as the relative compaction which is the percentage ratio of the field dry density (in-place dry density) to the maximum dry density as determined by a specific test method (standard

compaction such as the Proctor or modified Proctor compaction). Thus, the relative compaction can be expressed by the following equation (Holtz, 1990):

$$RC = (\gamma_d / \gamma_{dmax}) \times 100 \quad (1)$$

where RC , relative compaction (%); γ_d , dry unit weight; and γ_{dmax} , maximum dry unit weight for a given level of compaction effort [e.g., of modified Proctor (modified AASHTO) compaction].

For roadway subgrades and trench backfills, etc., there are typically codes specifying the minimum relative compaction that must be achieved. The guidelines typically specify that the field compaction must meet or exceed a certain level. For highways and airports, a minimum relative compaction of 95% of standard or modified Proctor is usually specified.

Note that the compaction effort for a compaction test is given by Eq. 2 according to Das (1990), as follows:

$$\text{Compaction effort (CE)} = \frac{W \times h \times N_b \times N_l}{V} \quad (2)$$

where W is the weight of the hammer; h is the drop height of the hammer; N_b is the number of blows per layer; N_l is the number of layers; and V is the volume of compacted soil.

3 Aim of the Study

The objective of this research is to show how water absorption, moisture distribution, and associated gypsum dissolution are affected by increasing compaction of gypsiferous soil samples subjected to long-term soaking. The increase of compaction effort is achieved by increasing the energy but at the same moisture contents for all soil samples under study. The moisture content adopted in this study is the optimum moisture content (optimum water content) of the modified Proctor (modified AASHTO) compaction.

4 Properties of the Tested Soil

The soil investigated in this research is a clayey gypsiferous soil obtained from a site in Iraq. The chemical and physical tests carried out on this soil indicate that the soil is a sandy lean clay of CL group according to the Unified Soil Classification System (ASTM D2487, 2017). According to AASHTO soil classification system (AASHTO T 88, 2017), the soil tested is A-6 (6).

During the particle size analysis of soils containing gypsum (using hydrometer test), the soil suspension usually flocculates partially or totally after a period of time, because of the calcium ions released from the gypsum (Vieillefon, 1979). Some researchers (Coutinet, 1965; Loveday, 1974) removed the gypsum from the soil before testing by using dilute HCl. However, this procedure may lead to unrealistic results and may change the physical properties of the gypsiferous soils with high gypsum content (Porta et al. 1986). Therefore, many researchers recommended the consideration of gypsum as an actual component of

the soil and not as a salt that has to be removed before carrying the hydrometer analysis (Porta et al. 1986). For this reason, the particle-size analysis of the tested gypsiferous soil was made using the method of Hesse (1974), which consists of coating the gypsum particles with a thin layer of barium sulphate, after a pretreatment of the sample with barium chloride (BaCl_2). The barium sulphate will prevent the gypsum dissolution in water during the hydrometer analysis. Thereafter, the particle size distribution was determined according to ASTM D 422-63 (2000). The particle size analysis result is presented in Table 1 revealing that the tested soil having about 73% fines.

The liquid limit (LL) and the plastic limit (PL) of the soil tested were 29% and 17%, respectively, when determined according to ASTM D4318 (2017). Thus, the plasticity index (PI) becomes 12%.

Using the density bottle method [B.S. 1377 (1990), test 6 (B)] with white spirit instead of water, the specific gravity of the soil tested was determined to be 2.47.

In order to obtain the moisture-density relation for the modified Proctor compaction test according to ASTM D 1557 (2012), a mold of 6" (152.4 mm) internal diameter and 7" (177.8 mm) height with 2" detachable collar is used. Figure 1 shows the moisture density relation of the compacted soil tested in this study. The peak of the compaction curve shown in the figure provides a maximum dry density of 18.18 kN/m³ at 11.75% optimum moisture content.

In addition, mineralogical study of the tested soil was carried out by using polarized microscope (Orthoplan). The test results are presented in Fig. 2. It can be seen from this figure that, in addition to gypsum (G), soil minerals such as calcite (C), glauconite (Gl), and quartz (Q) are present.

Regarding the total soluble salt contents, the procedure given by the US Department of Interior "Earth Manual" (1980), Appendix E8, has been followed with different soil/water ratios, namely, 1:10, 1:50, 1:100, 1:150, 1:200, and 1:225. It has been found that a dilution ratio of 1:50 recommended by the Earth Manual (1980) was not enough to dissolve all the soluble salts presented in the tested soil. A dilution of 1:50 yields a total soluble salts content of 12.5%, while the actual total soluble salts content is 35.1% taking place at a dilution of 1:200. Thereafter, the use of a soil/water ratio of 1:200 was adopted throughout this work.

The sulphate content as SO_3 was found to be 15.2% when tested according to "B.S. 1377 (1990), test no. 9". The gypsum content calculated from sulphate content was 32.6%. of the total soluble salts in the soil, gypsum accounted for 92.87%.

Table 1 Particle size analysis of the tested soil

Sieve no.	Particle size (mm)	% passing
4	4.76	100
10	2	99.8
40	0.42	93.68
100	0.149	79.5
200	0.074	73.4
Hydrometer analysis after Hesse (1974)	0.07	14.05
	0.055	6.65

Fig. 1 Modified Proctor moisture density relation of the compacted soil

Fig. 2 Cross nickle (XN) picture of the tested soil using polarized microscope (Orthoplan)

5 Preparation and Testing of Soil Samples

To study the effect of relative compaction and soaking periods on the water absorption and dissolution of gypsum from the compacted gypsiferous soil tested, two sets of CBR soil samples were prepared at optimum moisture content of the modified Proctor compaction test, namely, 11.75% as a molding water content. The first set of six pairs received a compaction effort of 2735 (kN m/m³) which is corresponding to modified Proctor compaction, while the second set of also six pairs was prepared at compaction effort of 586 (kN m/m³) which is equal that of standard Proctor. In other words, the compaction energy of the first CBR samples set was 4.56 times that of the second CBR samples set. Note that the average dry density of the second set of samples was 17.0 kN/m³. Thus, using Eq. 1, the relative compaction becomes 93.5%.

The two compaction efforts were chosen by changing the number of blows per layer of the soil sample compacted in a mold of 6" (15.24 cm) in diameter and 7" (17.78 cm) height (the sample diameter is 15.24 cm and 11.643 cm height). The soil in the mold is compacted by 10 lbs (4.54 kg) hammer falling from 18" (45.7 cm) height. The number of blows adopted was 56 and 12 for the modified and standard Proctor compaction efforts, respectively (see Eq. 2).

These samples were soaked for 0, 4, 7, 15, 30, and 120 days under 40 lbs (178 N) surcharge load.

Five samples for moisture content determination were collected from the top, quarter points, midpoint, and the bottom of each compacted soil sample after each soaking period. Subhi (1987) pointed out that the drying temperature for gypsiferous soil should not exceed 42 °C for 60 h. However, Horta (1989) reported that soil specimens containing gypsum should be dried to constant weight at a temperature lower than 60 °C, usually 50–55 °C, preferably 40 °C.

Accordingly, it was decided to use 40 °C as a drying temperature in this work. The soil specimens were dried until the dry weight became constant (usually after 5 days).

At the end of 4, 7, 15, 30, and 120 days soaking periods, the determinations of the TSS and gypsum content was carried out at five equal intervals along the soil samples compacted at OMC of 11.75% under the effect of 12 and 56 blows/layer and 40 lbs surcharge load.

6 Results and Discussions

6.1 Moisture Content Distribution

Figures 3 and 4 show the variation of moisture content along the compacted soil samples for 4, 7, 15, 30, and 120 days soaking for samples compacted at 56 and 12 blows/layer at 11.75% molding moisture content, respectively.

It is clear from Figs. 3 and 4 that the moisture content along the soaked compacted soil samples increases with decreasing compaction effort, and this can be attributed to the higher percentage of air voids and thus higher suction for samples compacted at low compaction efforts.

Figures 3 and 4 reveal also that the absorption of water during soaking at the top of the compacted soil samples is greater than that at the bottom for the chosen compactive efforts.

Fig. 3 Distribution of moisture content along the compacted soil samples at 56 blows/layer and 11.75% OMC

Figure 5 shows the effect of soaking period on the moisture content at the top and middle of compacted soil samples for the case of 56 and 12 blows/layer and 11.75% moulding moisture content. It is clear from this figure that the moisture content at the top of the compacted soil samples for the case of 56 and 12 blows/layer increases gradually with soaking period within the first month and remains generally almost constant thereafter. At the middle of the soil samples compacted with 12 blows/layer, similar phenomenon took place, but for samples compacted at 56 blows/layer, the moisture content at the middle of the compacted soil samples increased gradually at a slower rate.

Figure 6 shows the effect of compaction effort on the absorption of water of compacted soil samples during soaking for samples compacted at OMC of 11.75%.

Fig. 4 Distribution of moisture content along the compacted soil samples at 12 blows/layer and 11.75 %OMC

Fig. 5 Moisture content versus soaking period for different compaction efforts (case: top and middle of samples compacted at OMC)

It is clear from this figure that the samples compacted at 12 blows/layer absorb water 3.05 and 1.77 times the samples compacted at 56 blows/layer after 4 and 120 days soaking, respectively. This means that upon soaking, the ability to absorb water is greater for samples compacted at the lower compaction effort. The absorption of water

Fig. 6 Effect of compaction effort on water absorption of tested gypsiferous soil during long-term soaking

becomes slow upon soaking as the compaction effort increases. This can be attributed to the high density and hence low permeability achieved by high compaction effort.

6.2 Gypsum Distribution

Figures 7 and 8 show the effect of soaking period on the dissolution of TSS and hence gypsum at the top and bottom of soil samples compacted at OMC of 11.75%, respectively. It is obvious from these figures that the dissolution process is continuous at a significant rate even at 120 days soaking. In addition, these figures reveal that the TSS content is always higher than the corresponding gypsum content indicating that other soluble salts are present in small quantity beside gypsum.

However, the dissolution of gypsum at the top of the compacted soil sample is greater than that at the bottom, and this was attributed to the easier access of water to the sample from the top.

6.3 Correlations

A multiple correlation between absorbed water, soaking period and compaction effort has been developed as shown in Eq. 3 and a very strong correlation has been obtained with a coefficient of correlation $R = 0.9915$ (coefficient of determination $R^2 = 0.983$) for soaking period ≥ 4 days, as follows:

$$AW = 267 + 0.493 T - 0.0672 CE \quad (3)$$

Fig. 7 Effect of soaking period and compaction effort on the TSS and gypsum content at the *top* of soil samples compacted at OMC

Fig. 8 Effect of soaking period and compaction effort on the TSS and gypsum content at the *bottom* of soil samples compacted at OMC

where AW , absorbed water in gram; T , soaking period in day; and CE , compaction effort (energy) in kN m/m^3 .

Another multiple regression equation has been developed relating strongly the normalized average moisture content to the soaking period and compaction effort with $R = 0.963$ ($R^2 = 0.9281$), as given below:

$$M_T/OMC = 1.5866 + 0.00138 T - 0.0001437 CE \quad (4)$$

where M_T , average moisture content along CBR soil sample at soaking period T , in %; OMC , optimum molding moisture content in %, in this case 11.75%; T , soaking period in day; and CE , compaction effort (energy) in kN m/m^3 .

Note that at the top of CBR soil samples, the gypsum content decreased by 14.7% and 18.393% after 120 days soaking for CBR soil samples compacted at 56 blows/layer and 12 blows/layer, respectively. At the bottom of CBR soil samples, the gypsum decreased by 12% and 17.24% after 120 days soaking for CBR soil samples compacted at 56 blows/layer and 12 blows/layer, respectively.

A multiple regression analysis has been developed relating the decrease in gypsum content along the CBR clayey soil samples with compaction effort and the increase in average moisture content along the CBR due to soaking for ≥ 4 days, as shown below:

$$G_T/G_U = 1.695 - 0.0554 * CE - 0.48 M_T/OMC \quad (5)$$

where G_T , average gypsum content along CBR soil sample at soaking period T , in %; G_U , initial gypsum content before soaking in %; M_T , average moisture content along CBR soil sample at soaking period T , in %; OMC , optimum molding moisture content

in %, in this case 11.75%; and CE , compaction effort (energy) in MN m/m^3 , namely, 2.735 MN m/m^3 and 0.586 MN m/m^3 for this study.

Figure 9 shows the predicted G_T/G_U from Eq. 5 as compared with the measured G_T/G_U . It can be seen from Fig. 9 that the predicted values match well the measured values with high multiple correlation coefficient of 0.9456 ($R^2 = 0.8943$) indicating a strong correlation after Anderson and Sclove (1978).

According to Eq. 5, it can be seen that the average gypsum content along CBR soil samples is affected significantly by the increase in moisture content, namely, ten times its effect by increasing the compaction effort adopted in this study. This emphasizes the dangerous effect of water on gypsiferous soils.

7 Conclusions and Recommendations

This paper studied the effects of compaction and soaking conditions including compaction effort and soaking period on the water absorption and gypsum dissolution of compacted gypsum-rich clayey soil. Two sets of CBR samples were prepared at the optimum water content of modified AASHTO compaction. The first set received 100%, while the second set received 93.5% relative compaction. The soil samples were subjected to different soaking periods and at the end of each soaking period, both the moisture contents and gypsum contents were determined. The paper shows that the moisture content and the gypsum content distributions are not uniform along each sample at the end of each soaking period. The water absorption and gypsum dissolution decrease with increasing relative compaction as the soil becomes denser.

The main conclusions of this work can be summarized as follows:

- 1- For each compaction effort, the moisture content along each soil sample increased with increasing soaking period. This increase in moisture content is much more

Fig. 9 3D Correlation between measured and predicted G_T/G_U

- pronounced in soil samples compacted at the lower relative compaction. Accordingly, higher relative compaction is strongly recommended in practice.
- 2- The distribution of moisture content along the compacted soil samples after each soaking period and for each compaction effort is not uniform. The moisture content at the top of each soil sample is greater than at the bottom, and the least moisture content took place at the middle of the sample. Accordingly, for regions with hot dry climate and low probability of wetting, the effect of short showers of low frequency is insignificant.
 - 3- Soil samples compacted at 12 blows/layer absorb water 3.05 and 1.77 times the samples compacted at 56 blows/layer after 4 and 120 days soaking, respectively. Upon soaking, the ability to absorb water is greater for samples compacted at the lower compaction effort. In practice, an increase in relative compaction of gypsum-rich soils improves the soil by reducing its ability to absorb water. This fact can also have an important bearing for geotechnical engineers working on expansive soils containing sulphate.
 - 4- For the chosen compaction efforts, the dissolution of salts and hence gypsum, at the top of compacted soil samples, was greater than that at the middle for samples compacted at OMC. Little decrease in the TSS took place at the middle of the soil samples compacted at OMC even at the end of 120 days soaking indicating that in practice, short wetting periods with low frequency are of little or no significance.
 - 5- For the chosen compaction efforts, the dissolution of TSS and hence gypsum increased with increasing soaking period. At the end of 120 days soaking, the dissolution process did not stop. The average gypsum content along CBR soil samples decreased by 9.9% and 14.8% from its initial value after 120 days soaking for CBR soil samples compacted at 56 blows/layer and 12 blows/layer, respectively. In terms of the average gypsum content, increasing the compaction effort by 4.56-fold reduced gypsum dissolution by 1.06-fold at the end of 120 days soaking.
 - 6- The developed multiple regression equation relating the normalized average moisture content to the soaking period and compaction effort is strongly recommended for gypsum-rich clayey soils only.

Notation AW Absorbed water in gram,

CE Compaction effort (compaction energy)

G_s Specific gravity

G_T Average gypsum content along CBR soil sample at soaking period T

G_U Initial gypsum content before soaking

h Drop height of the hammer

LL Liquid limit

M_T Average moisture content along CBR soil sample at soaking period T

N_b Number of blows per layer

N_l Number of layers

OMC Optimum moisture content (optimum water content)

PI Plasticity index

PL Plastic limit

RC Relative compaction

T Soaking period in day

TSS Total soluble salts

V Volume of compacted soil

W Weight of hammer

d Dry unit weight

d_{max} Maximum dry unit weight at the optimum moisture content of a compaction curve

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