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ORIGINAL PAPER

Effect of gypsum crystals on the pavement design properties of a clayey soil

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Abstract

Gypseous soils are present in many parts of the world, particularly in the Middle East and Africa. While effects of addition of various percentages of gypsum on the engineering properties of soils have been investigated previously by many researchers, effects of presence of naturally occurring gypsum crystals on soil properties have been less studied. Study of these effects is important since many civil engineering developments need to be carried out in or on soils containing naturally occurring gypsum crystals. These crystals consist of fragile particles that break easily, even during handling and laboratory testing, and their presence affects many properties of in situ soils. Moreover, estimation of the percentage of crystallized gypsum in such soils usually requires unconventional chemical or physical tests since visually estimated percentages are often misleading due to the transparent nature of the crystal grains, especially when mixed with fine-grained soils. The current study presents results of tests on a low-plasticity clayey soil containing gypsum crystals. Percentages of crystals present in the soil are determined using a simple procedure involving water content determination of the soil dried at 110 and 40 °C. Effects of crystalized gypsum content on the in situ and laboratory properties of the clayey soil are studied, and results are discussed in the context of pavement design. It is shown that in situ soil unit weight, field CBR, plasticity, grains specific gravity, maximum dry density and optimum moisture content decrease with the increase in the gypsum crystal content of the soil.

Keywords Gypsum · Pavement design · Fine-grained soil · Soil properties · Gypsum crystal

Introduction

Presence of gypsum in soils and its consequences

Various forms of calcium sulfate or gypsum are found to extend over more than 20% of the surface of the earth. The mineral gypsum may occur both as a geologic deposit and as a soil constituent. It has two molecules of water and is represented by the formula $CaSO_4.2H_2O$ as shown in Fig. 1. Its solubility is 2.6 g/l of distilled water at 25 °C and 101 kPa pressure. Solubility of the gypsum that is contained in soils depends on the other salts that are also present in the environment. At temperatures above 40 °C, dehydration of gypsum commences, causing the first 1½ molecules of water to evaporate. This dehydration continues up to a temperature of about 65 °C and leads to the formation of calcium hemihydrate or basanite ($CaSO_4.½H_2O$). Even when temperature reaches about 70 °C, the $½H_2O$ in basanite still remains attached relatively strongly but at about 95 °C, it is lost leading to the formation of calcium anhydrite ($CaSO_4$) (Kuttah and Sato 2015).

Naturally occurring soils with gypsum are often found where gypsum-containing (i.e. gypseous or gypsiferous) geologic deposits are present, sometimes even in deep-seated or distant deposits relative to the site of the gypsum-containing soils. Due to some solubility of gypsum in water, groundwater containing calcium sulfate may crystallize, and gypsum crystals may appear within the soil. The presence of gypsum crystals, with their specific physicochemical properties which differ sharply from the properties of other soil minerals, complicates the determination of water content, solid particles specific gravity, grain-size distribution, plasticity, strength and deformation properties, and other

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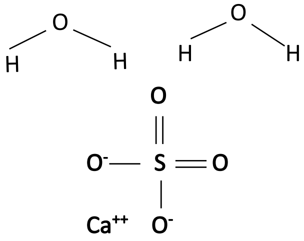


Fig. 1 Chemical structure of gypsum

parameters needed for engineering design (Arakelyan 1986). Jafarzadeh and Burnham (1992) studied various shapes of gypsum crystals developed in different environments and concluded that it is difficult to relate the shapes and arrangements of the crystals to the environment due to the complexity and variability of these shapes and arrangements.

Features of gypsum crystals found in various parts of the world depend, among other factors, on the moisture and properties of the soils in which they are developed (Hashemi et al. 2011; Ageeb et al. 2015).

Jha and Sivapullaiah (2017) conducted detailed review of various forms of gypsum present in nature and their transformations. They indicated that methods proposed to determine gypsum content are based on the indirect measurement of the concentration of Ca^{2+} or SO_4^{2-} ions through different techniques. Moreover, analytical techniques such as thermogravimetric analysis (TGA), portable X-ray fluorescence (PXRF), X-ray diffraction (XRD) and scanning electron microscopy (SEM) are proposed for qualitative, semi-quantitative and quantitative determination of gypsum present in soils. However, the complexity and limitations involved in most of these methods enforce the soil scientist and geotechnical engineer to use easier and more direct techniques for the determination of gypsum in soils.

Most soil surveys lack sufficient information about the presence and properties of gypseous soils at project sites, and the need for such information is of great importance. The presence of gypseous soils under a construction area may be dangerous due to the collapsible nature of these soils in the presence of water. Damage to roads and pavements at ground surface may occur particularly when groundwater is high and where soluble materials are present near ground surface. Remarkable evidence is available on the failure of dams, highways and some other structures constructed above gypsiferous soils or rocks (Solis and Zhang 2008). On the other hand, soils and rocks containing gypsum can change their properties in the presence water, pressure and heat. When gypsum is present in the soil or rock in large amounts, it controls its properties and may have adverse or favorable effects on its engineering and agricultural properties (Wei et al. 2020; Fattah and Dawood 2020; Rodríguez-Rastrero and Ortega-Martos 2022). On the other hand, in some instances, gypsum is added to soils to improve some of their engineering properties. Therefore, depending on the type of the base soil and percentage of the gypsum present, gypsum can have both detrimental and beneficial effects on the properties of soils.

Engineering properties of gypseous soils

Kifae (2010) indicated that the CBR of soils decreases due to the presence of gypsum, but this decrease may be compensated by increasing surcharge, which densifies the soil. Razouki and Salem (2014) presented the (CBR) and effect of changes in the moisture content of a roadbed sand with a gypsum content of about 39% subjected to cyclic soaking and drying. They concluded that for each cycle, the CBR decreases during soaking and increases during drying for all frequencies of the applied cycles.

Moret-Fernández and Herrero (2015) presented test data on the effect of gypsum content on the saturation of soils as demonstrated by changes in their Water Retention Curves (WRC). They indicated that soils with high gypsum content have a WRC with higher water retention near saturation and steeper WRC slopes.

Azam and Abduljauwad (2000) investigated the effects of addition of up to 20 gypsum and anhydrate, and Yilmaz and Civelekoglu (2009) examined effects of addition of up to 10% gypsum on the plasticity and swelling characteristics of the expansive clayey soils they tested. They concluded that lower Atterberg limits, plasticity indices and expansion potentials are obtained as the percentage of gypsum added to the clayey soils increases.

Following comprehensive study of previous research on the behavior of gypseous soils, Kuttah and Sato (2015) indicated that adding gypsum to soils may increase their maximum dry density and decrease their optimum moisture content (OMC). This was previously reported by Kamei et al. (2012) and Ahmed (2013), who also indicated that this conclusion is valid only for gypsum contents ranging from 0 to 15%. For gypsum content of more than 15%, he observed a decrease in the maximum dry unit weight and an increase in the OMC. Razouki and Kuttah (2021) obtained compaction curves with double peaks and two maximum dry densities and two OMCs for a sandy clay soil containing 33% gypsum in a standard AASHTO compaction test.

Gypsum may be added to weak non-gypseous soils in recommended quantities to improve their engineering performance. Kuttah and Sato (2015) indicated that the best soil strength performance can be achieved by adding 15 to 20% gypsum to sandy soils and 20 to 25% gypsum or basanite to clayey soils. These percentages of added gypsum and/or basanite are generally consistent with those recommended to get maximum dry unit weight and OMC of stabilized soils by Ahmed (2013). Razouki and Kuttah (2021) presented results of unconsolidated undrained (UU) tests on un-soaked and 120-day soaked samples in fresh water for a compacted sandy lean clay having a total soluble salt content of 35% and a gypsum content of 33%. They observed sharp decrease in cohesion and internal friction angle of the soil due to long-term soaking. Based on results of their experimental study, Abid Awn and Abbas (2021) concluded that substantially greater footing settlement and lower hydraulic conductivity, leading to increase in pore water pressure, are experienced by gypseous soils when they are subjected to vibration and shaking.

It may be noticed from the studies described previously that the majority of these studies examine changes in soil properties resulting from the addition of gypsum to soils to improve their properties, and their results are not always the same. Moreover, these studies do not examine effects of presence of relatively high percentages of naturally occurring “gypsum crystals” on the engineering properties of soils. These crystals form mostly larger size, fragile grains that break even during handling and grain size determination tests. Effects of presence of these crystals that have geologically formed over the years are expected to be substantially different from the effects of gypsum recently added to alter soil properties.

This paper presents results of in situ and laboratory tests conducted on a low-plasticity clayey soil containing various percentages of gypsum crystals. The tested gypseous soil was found in an airport site in which runway pavement damages were observed and improvements were planned. Various in situ and laboratory tests were conducted on soils containing various percentages of gypsum crystals, and changes in soil properties as a function of the percentage of gypsum crystals were obtained and the results are discussed. A simple and straightforward method to determine the percentage of crystalized gypsum in naturally occurring soils using water contents measured at 40 and 110 °C is used, and the results are compared with approximate percentages obtained based on observations of color changes after drying. A similar approach was also presented by Al Mufty and Nashat (2000) and was verified by comparing its results with those obtained from chemical tests for the determination of gypsum percentage in soils.

The soil tested

A total of 13 test pits were excavated in an airport site in the Fars province in the mid-south region of Iran, where damages to the runway pavement, including settlements and crackings, were observed. Detailed description of the geological and geomorphological features of this province are described by Hashemi et al. (2011). Twelve of the test pits, TP7 to TP18, were excavated to a depth of 1 m, and one test pit, TP19, was extended to 5-m depth below ground surface to explore the possible presence of groundwater. A site plan showing the runway and locations of the test pits is provided as Fig. 2. In situ testing and soil sampling were conducted at soil surface and at 30, 60 and 100-cm depths in the 1-m deep test pits, and in 1-m depth intervals in the 5-m deep test pit. The site soil consists mostly of low plasticity sandy clay with sublayers and inter-beds of silty and clayey sand mostly at shallower depths. Measured percentage of sand in the low plasticity clay varied from 10 to 45% and plasticity index of the clay samples with no gypsum content varied from 10 to 19%. Test pits TP7 to TP14 were excavated adjacent to the runway pavement, TP15 to TP18 at a few meters away from the runway and TP19, excavated to 5-m depth, a few hundred meters away from the runway pavement. In the test pits adjacent to the runway, gravelly soils used as base and sub-base for the runway pavement were also encountered at ground surface. Table 1 shows the soil types encountered at various depths in the test pits and their properties, and Fig. 3 shows the grain size distributions of the low plasticity clayey soils that are the subjects of the current study. It is noted that where the site soils consisted of high percentages of gypsum crystals, gradation tests were not conducted since grain sizes continuously changed due particle breakage during testing and handling and no reliable results could be obtained. Data for TP8 and TP15 are not presented for brevity since the soils in these locations consisted of silty sand with no gypsum crystals and were therefore not relevant to the current study.

Fig. 2 Site plan showing locations of the test pits relevant to airport runway

Table 1 Test data used for determination of gypsum crystal content of various samples of fine-grained (CL) soils

Test pit no	Sample depth (cm)	In situ wet density (%)	w_{110} (%)	In situ dry density (kN/m^3)-110 °C	Visual estimate of color change (%)	Soil type	W_{40} (%)	Calculated gypsum crystal content (%)	Avg. of visual gypsum content (%)
7	0	20.9	2.35	20.5	0	GW-GC	2.35		
	23					SC-SM			
	30	16.0	4.85	15.3	0	CL	4.85		
	60	15.0	22.0	13.0	60–40	CL	8.0	54.91	50
	100	15.3	18.76	12.9	30–50	CL	10.0	35.29	40
9	0	22.3	3.08	21.6	0	GW-GC	3.08		
	15	0.0				CL		50	
	30	16.0	13.56	12.2	30–50	CL	5.0	36.07	40
	60	14.8	10.3	13.4	0–20	SM	6.0		10
	100	16.0	8.08	14.8	0 to 10		6.0		5
10	0	20.7	8.97	19	10 to 20	SC-SM	3.0		15
	10	0.0				CL			
	30	15.8	20.08	11.6	60–80	CL	6.0	56.1	70
	60	15.2	17.07	12.9	30–50	CL	8.0	39.43	40
	100	17.2	20.01	14.3	30–50	CL	10.0	39.91	40
11	0	21.0	2.55	20.5	0	GP-GM	2.55		
	16	0.0				CL		80.0	
	30	15.1	27.47	11.9	70–90	CL	6.0	80.59	80
	60	15.0	28.66	11.7	70–90	CL	8.0	76.83	80
	100	16.3	24.91	13.1	60–80	CL	10.0	57.11	70
12	0	22.2	2.72	21.6	0	SC-SM	2.72		
	25					SC-SM			
	30	16.5	19.35	13.8	40–60	CL	6.0	53.52	50
	60	16.3	18.45	13.7	20–40	CL	8.0	42.21	30
	100	16.3	23.52	13.2	50–60	CL		52.37	55
13	0	20.0	2.89	19.4	0	SC			
	13					CL			
	30	15.6	24.63	12.6	50–70	CL	6.0	71.52	60
	60	16.0	25.3	14.4	30–50	CL	10.0	58.42	40
	100	15.6	23.85	12.6	30–40	CL	12.0	45.78	35
14	0	20.1	2.85	19.5	0	GC-GM			
	15	0.0				GC			
	30	19.5	9.65	17.8	0	SC	9.0		
	60	18.0	15.67	16.8	0	CL	15.0	2.77	0
	100	16.3	18.95	15.0	0–20	CL	18.0	3.82	10
16	0					CL		45.0	
	30	16.0	17.82	14.0	30–50	CL	6.0	48.0	40
	60	15.3	19.82	12.8	40–60	CL	8.0	47.2	50
	100	17.0	19.38	14.2	30–50	CL	10.0	37.59	40
17	0					GC-GM			
	30	13.9	27.06	10.9	50–60	SC	9.0	68.01	55
	60	15.3	22.87	12.5	40–60	CL	8.0	57.91	50
	100	17.0	23.86	13.0	40–50	CL	10.0	53.54	45
18	0					CL		0.0	0
	30	16.3	8.51	15.0	0	CL	8.51	0.0	0
	60	16.6	9.88	15.1	0	SC-SM	9.88		
	100	15.6	4.84	14.9	0	SC-SM	4.84		

Table 1 (continued)

Test pit no	Sample depth (cm)	In situ wet density (%)	w_{110} (%)	In situ dry density (kN/m^3)-110 °C	Visual estimate of color change (%)	Soil type	W_{40} (%)	Calculated gypsum crystal content (%)	Avg. of visual gypsum content (%)
19	100				20–40	CL	9.6	29.19	30
	200				30–50	CL	11.55	34.51	40
	300				0–20	CL	17.36	12.85	10
	400				0–10	CL	17.31	5.36	5
	500				0	CL	18.37	0.61	0

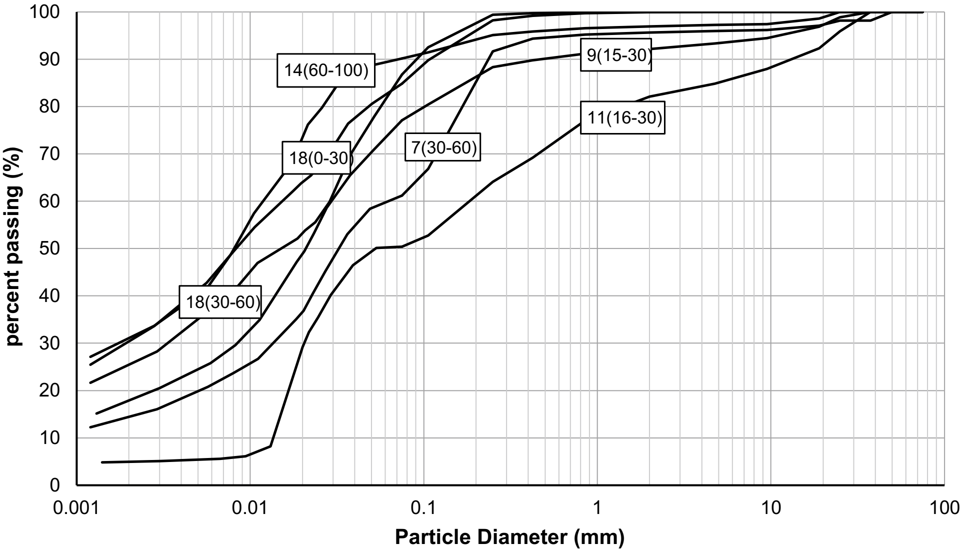


Fig. 3 Grain size distributions of the clayey soils at various site locations. Test pit numbers and sample depth intervals (in parenthesis, cm) are shown on each curve

Gypsum crystals ranging in size from fine (passing sieve #200) to coarse gravel size were observed in the site soil as shown in Fig. 4. As part of the in situ investigation program, field density and moisture determination and field CBR testing were completed, and the samples collected were transferred to the laboratory for testing. A comprehensive laboratory testing program was conducted with some of the results presented and discussed in subsequent sections of this paper. Groundwater was not encountered during the excavation of up to 5-m depth and is believed to be at greater depths.

Fig. 4 A sample of gravel and finer sized gypsum crystal particles found in the site soil

Determination of gypsum crystal content in the soil samples

Clearly, in cases where the soil is mixed with gypsum to study its effect on soil properties, gypsum percentage in the soil is known. However, determination of gypsum crystal content in natural soils presents a challenge often requiring specialized, costly and time-consuming tests such as chemical analyses, SEM observations, statistical analyses, etc. A simple and straightforward procedure is used in the current study for the determination of gypsum crystal content in the natural soil samples by measuring water contents of the sample after drying it at 110 and 40 °C. This method is based on the well-known thermogravimetric analysis (TGA) procedure proposed and used successfully before by a number of researchers such as Nelson et al. (1978), Al Mufty and Nashat (2000) and Kifae (2010). However, researchers usually used relationships based on weights of samples dried at difference temperatures, while the current study uses a relationship based on water contents measured at different temperatures since these results were available in the current project.

When drying the soil at 110°, both free water existing between soil and crystal grains and water participating in forming the gypsum crystals are evaporated, but when drying at 40°, only free water is evaporated and the gypsum crystals are not de-hydrated. Water contents obtained by drying the samples at 110 and 40° are referred to here as w_{110} and w_{40}, respectively. Values of w_{110} and w_{40} are termed here as "apparent water content" and "actual water content" respectively, since the former value includes the crystallization water, which is not actually part of the moisture contained in the soil pores. The mentioned water contents are expressed here in decimal fractions (between 0 and 1) rather than percentages (between 0 and 100) for simplicity.

The molecular weight of crystalized Gypsum ($CaSO_4 \cdot 2H_2O$) is 172.17 g/mol and that of the anhydrate (gypsum without the crystalization water), or ($CaSO_4$) is 136.14 g/mol. Therefore, the gypsum crystals lose 20.9% of their weight due to de-hydration. In a sample of naturally occurring wet soil containing gypsum crystals, if total weight of the dry sample containing gypsum crystals is unity and weight of the dry crystals alone is G, upon drying this sample at 40°, weight of the water lost will be w_{40}, and upon drying at 110°, total weight of the water lost will be $(0.209G + w_{40})$ and the remaining weight of the soil upon drying at this temperature is $(1 - 0.209G)$. In this case, the "apparent water content" will be

$$w_{110} = \left(w_{40} + 0.209G\right)/(1 - 0.209G) \tag{1}$$

In the above equation, G is the fraction by weight of the gypsum crystals in a sample dried at 40° and the fraction of soil without crystal will be $(1 - G)$. Assuming that the actual water content of the crystals and the soil particles is the same, and solving Eq. 1 for G, the fraction of crystalized gypsum in the sample will be:

$$G = 4.78\left(w_{110} - w_{40}\right)/\left(1 + w_{110}\right) \tag{2}$$

Percentage by weight of the gypsum crystals in the naturally occurring soil will then be 100G. It is noted that the color of transparent gypsum crystals changes into white following drying at 110 °C. Approximate percentage of color change in each sample may be used to visually estimate the percentage of gypsum in that sample following drying at 110 °C. Therefore, samples dried at 110 °C were carefully inspected, and their color changes were estimated by comparing colors of pairs of samples as shown in Fig. 5. In order to verify the gypsum contents obtained from Eq. 2, measured values of w_{110} and w_{40} for the clayey soil samples were used to calculate gypsum percentages using this equation, and the results were compared with the percentages estimated from the color change observations of

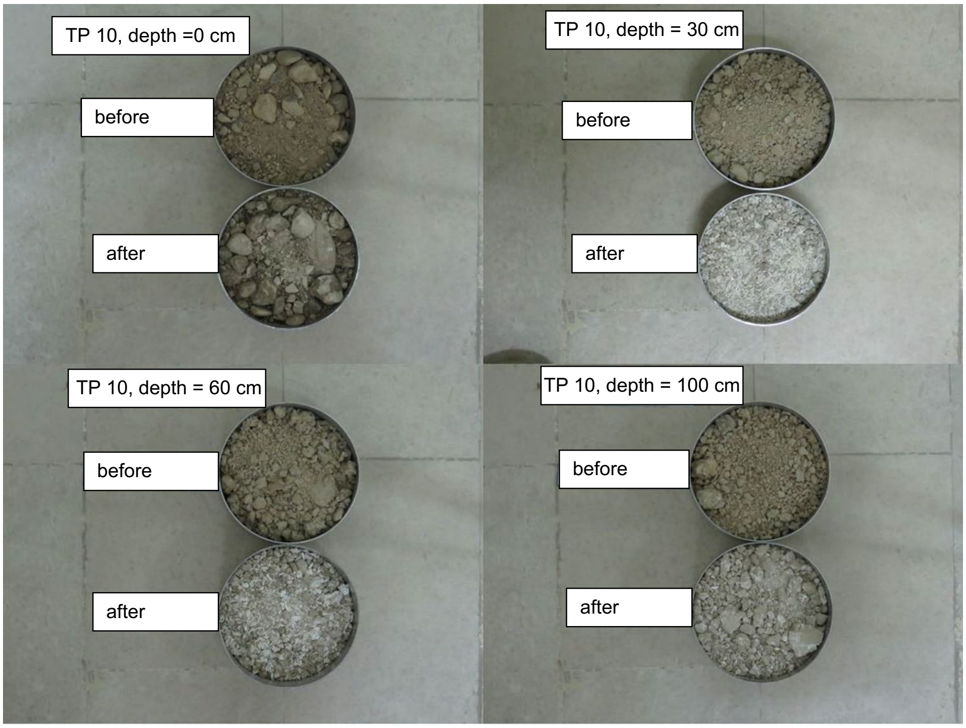


Fig. 5 Samples of soil color change comparisons before and after drying at 110 °C at various depths of TP10

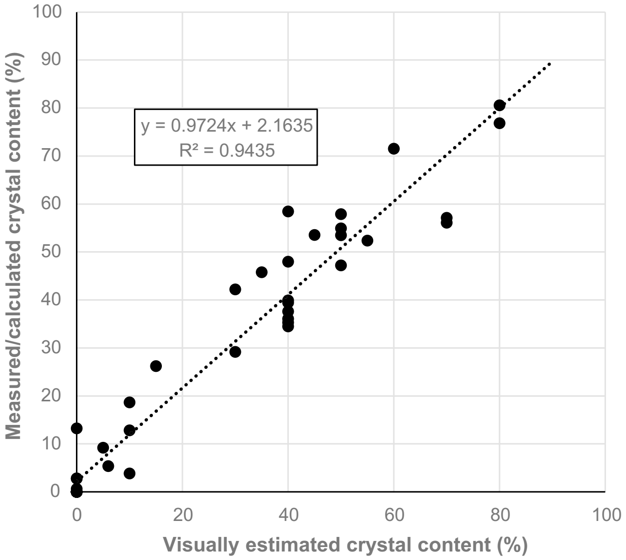


Fig. 6 Comparison of calculated (Eq. 2) and visually estimated gypsum contents of various site soil samples

the same samples and results of this comparison are shown in Fig. 6. Data used in these calculations are shown in Table 1. It is noted that while the w_{110} values were measured for all of the samples collected during the site investigation, the w_{40} values were measured later for some of the samples after transferring them to the laboratory using moisture-tight containers. Therefore, calculation of gypsum content using Eq. 2 was possible only for these samples, and numerical values of these results are shown in Table 1. As shown in Fig. 6, although some scatter is observed, relatively consistent values of gypsum content are obtained from the calculated and visually estimated methods. Verification of this TGA method was also presented by Al Mufty and Nashat (2000) through comparison with results obtained from chemical analysis. These results indicated that where gypsum is present in clayey soils such as Montmorillonite, heating up to 45 °C may not be sufficient to evaporate all moisture, and therefore, this method may not lead to accurate results in such soils. However, the method is reliable in low-plasticity, low water content Kaolinite-based soils such as those examined in the current study, especially when gypsum content is more than about 30%.

Effects of gypsum content on the various soil properties

Formation of gypsum crystals in the various site soils

Effects of presence of various percentages of gypsum crystals on the engineering properties of the fine-grained gypseous site soils are examined in this section. Careful examination of the data shown in Table 1 indicates that, interestingly, gypsum crystals have mostly formed in the fine-grained clayey site soils and are non-present or are at low percentage in the coarser grained sandy soils even when they are at the same depth and location as the clayey soils. This may be due to the higher water content typically present in the in situ clayey soils and the crystallization of the dissolved gypsum present in this water content. It is noted, however, that where gypsum crystals are formed in coarser soils, they have grown into greater sizes and are more visible as shown in Fig. 4, while those formed in the fine-grained soils were hardly visible or invisible, and could be fully noticed only after drying the soil samples up to 110 °C, which caused a change in the color of the crystals from transparent to opaque white.

Since as mentioned above, gypsum crystals were mostly observed in the low plasticity clayey soils, and that engineering properties and design parameters of these soils are different from those of the site sandy soils and data from the two soils cannot be combined during study of the effects of gypsum crystal contents, only results from the clayey soils are examined in the current study. Data obtained from various tests on the site clayey soils are plotted to determine gypsum crystal effects on the soils properties. Numerical values of the data used for these studies are shown in Table 1, standards used in conducting the tests are shown in Table 2, and results of the tests are provided in Table 3 for ease of reference.

In situ densities

Due to the smaller specific gravity of gypsum with $G_s = 2.32$ (Kifae 2010) compared to the soil grains, presence of higher percentages of gypsum crystals in the in situ soils leads to lower unit weight of these soils. Figure 7 shows changes in the wet density of in situ soils containing various percentages of gypsum crystals. Moisture contents obtained for determination of the wet unit weights are obtained by drying samples at 40 °C, and this causes the evaporation of only the pore water present in the voids between the soil and gypsum

Table 2 Standards used for testing the soil samples

Standard number	Test for which standard was used
ASTM D422-63(2007) e2	Grain size distribution
ASTM D4318-17e1	Atterberg limits determination
ASTM D2216-19	Laboratory determination of moisture content
ASTM D854-14	Specific gravity determination
ASTM D698-12(2021)	Compaction testing
ASTM D4429-04	Field CBR test
ASTM D1556	Determination of in situ soil density

Table 3 Test results used for the study of the effect of gypsum crystal content on the various soil properties

Test pit no	Sample depth (cm)	Fines content (%)	Soil type	PI	Gs	Max dry density (kN/m^3)	OMC (%)	Field CBR
7	0	11	GW-GC	4	2.64	21.2	7.8	
	23	19	SC-SM	4	2.7	21.3	8.3	
	30	61	CL	15	2.75	18.3	13.9	
	60	64	CL	12				
9	0	12	GW-GC	4	2.67	21.5	6.3	
	15	77	CL	13	2.69	18.3	14.3	
	30	50.5	CL					
	60	41	SM	0	2.65	17.4	13.7	
10	0	21.5	SC-SM	7	2.66	19.7	8.8	
	10	61.6	CL	7				
	30	60	CL	9	2.51			
	60	51	CL	10				
11	0	9.5	GP-GM	3	2.65	21.3	6.1	
	16	50.3	CL	8	2.49	17.3	14	
	30	60	CL	8				
	60	65	CL	6				
12	0	12.6	SC-SM	4	2.66	21.1	8.5	
	25	19.2	SC-SM	6	2.68	21.4	6.3	
	30	54.2	CL	10				
	60	56.9	CL	12				
13	0	20.1	SC	9	2.68	20.8	7.9	
	13	54.3	CL	11	2.58			
	30	70	CL	7				
	60	76.4	CL	9				
14	0	15	GC-GM	5	2.68	21.5	8	
	15	18.6	GC	10	2.69	20.3	10	
	30	27	SC	10	2.68	19.8	10.2	
	60	90	CL	16	2.7	18	17.8	
16	0	57.6	CL	10	2.56	17.5	15	
	30	60.6	CL	11	2.52	17.0	15.2	30
	60	69	CL	12				
	100		CL					43
17	0	18	GC-GM	6	2.68	20.7	8.8	
	30	36	SC	11	2.52	16.6	16.4	11
	60	74	CL	11				15
	100		CL					12
18	0	85	CL	15	2.69	18.1	17.1	
	30	87	CL	15	2.69	17.4	17.2	16
	60	48	SC-SM	4	2.7	17.7	13.8	22
19	100		CL	12				
	200		CL	14				40
	300		CL	16				
	400		CL	13				
	500		CL	12				

crystal grains while leaving the crystallization water inside the crystal grains unchanged.

It may be noticed from Fig. 7 that while in situ density of soils with no gypsum crystal varies between 16 and 18 kN/m^3, soils with about 70 to 80% gypsum crystals have in situ densities ranging from 15 to 15.6 kN/m^3. Due to the fragile nature of the gypsum crystal grains, it is expected that higher percentages of gypsum lead to higher settlements of the soil

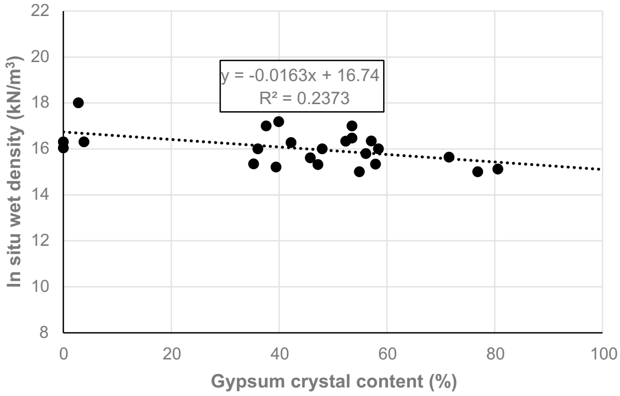


Fig. 7 In situ wet densities of the site clayey soils containing various percentages of gypsum crystals

under applied loads. This behavior will be discussed during presentation and discussion of the results of the in situ California Bearing Ratio (CBR) tests. This is in addition to the possibility of dissolution of the gypsum soaked due to rise of the groundwater level or capillary action.

Figure 8a, b compares dry unit weights of the in situ soil when dried at 110 °C and 40 °C, respectively. Figure 8a indicates that density decreases at a steeper slope with crystalized gypsum content compared to the wet density, when drying occurs at 110 °C, and this is clearly expected since as crystal content increases, percentage of crystallization water present in a unit volume of soil increases and this water is lost during drying at 110 °C, causing greater decrease in the weight of a unit volume of the dried soil. Dry density in this case varies from a value as low as 11.6 kN/m^3 to a maximum of 16.8 kN/m^3.

On the other hand, when soils are dried at 40 °C, in situ density decreases slightly with increase in crystal content as shown in Fig. 8b, with values ranging from a minimum of 13.8 kN/m^3 to a maximum of 15.6 kN/m^3. Although a general decrease in dry density with crystal content is observed, these densities vary within a band of approximately 14 to 16 kN/m^3 for each crystal content, likely due to differences in the degree of compactness and sand content of soils having the same crystal content tested at various locations of the site. On the other hand, comparison of Fig. 8b with Fig. 7, which shows greater decrease in wet density with crystal content, indicates that the in situ clayey soils with greater crystal content accumulate less water in their pores compared to those with less crystal content, and this leads to greater decrease in their in situ wet density with crystal content compared to the in situ dry density obtained from the w_{40} measurements. In other words, these results indicate that in situ wet density of gypseous soils decrease with increase in the gypsum content both due to the smaller specific gravity of gypsum crystal grains, and due to the retention of less water in their pores. This result may seem inconsistent with the conclusions of Moret-Fernández and Herrero (2015) reported earlier in "Engineering properties of gypseous soils'' section. However, in their paper, they indicated that the water content at saturation did not appear to be much affected by gypsum content, and some of their data actually showed somewhat lower water contents at saturation for soils with higher gypsum contents. Moreover, they recommended further research on soils at "structured field conditions," and the data in the current study was obtained from tests on samples collected from the field and having natural water contents.

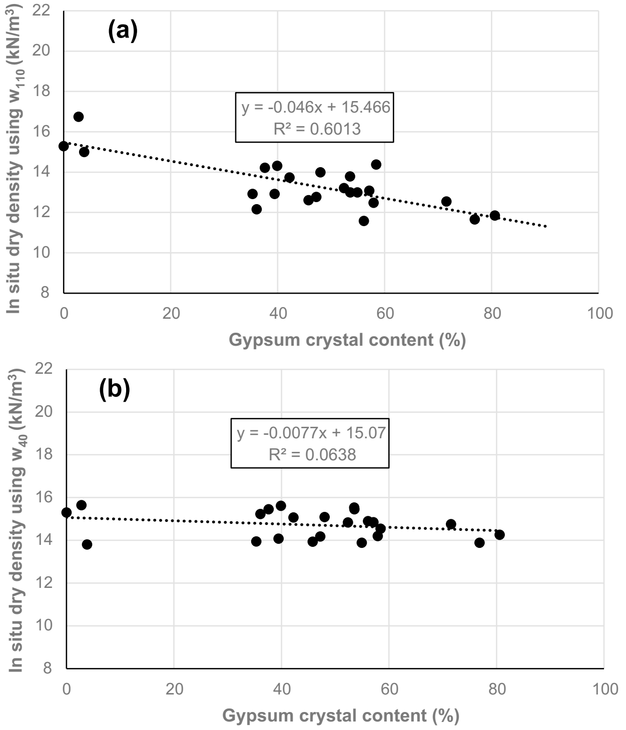


Fig. 8 In situ dry densities of the site clayey soils having various percentages of gypsum crystals obtained by drying samples at (**a**) 110 °C and (**b**) 40 °C

Soil plasticity

Figure 9 shows changes of plasticity index (PI) of the in situ clayey soils with the percentage of gypsum crystals. It may be noted that soil plasticity decreases significantly with the increase in gypsum crystal content. This may be attributed to the non-plastic nature of the crystal grains, which causes decrease in plastic behavior of the low-plasticity clayey soils as crystal content increases. While PI of samples with no gypsum crystals varied between 12 and 16%, values for samples with about 80% gypsum crystals dropped to a range

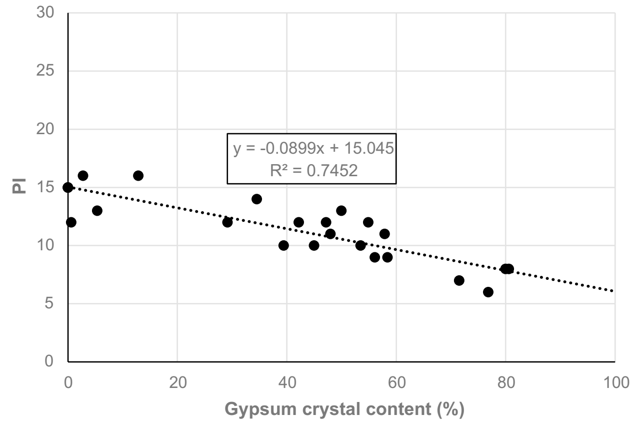


Fig. 9 Variation of plasticity index (PI) of the site clayey soils with the changes in their gypsum crystal content

of about 6 to 8%. Similar trends were observed in the variation of liquid limits and plastic limits, but these values are not reported here for brevity. It is noted that in determining water contents for the Atterberg limit tests, soil samples were dried at 40 °C such that the crystallization water was not lost during the water content determination.

The results described above are consistent with those reported by Azam and Abduljauwad (2000) and Yilmaz and Civelekoglu (2009) described earlier in "Engineering properties of gypseous soils'' section. However, unlike these two studies, in the current study, the gypsum was not present in the soil as an additive, but it naturally developed over time within the soil in the form of crystals, and its amount was substantially greater than the maximum 10 and 20 percentages added to the base soil in the mentioned two studies.

Soil grain specific gravity

The specific gravity of gypsum grains is about 2.32 (Kifae 2010), which is significantly smaller than those of soil solid grains (Gs) which typically varies within a range of 2.6 to 2.8. Therefore, it is expected that in situ soils containing gypsum crystals will have smaller grain specific gravity as gypsum crystal content increases. Figure 10 shows variations of grain specific gravity with gypsum content measured for the clayey soil samples collected from the airport site. The figure indicates a substantial effect of gypsum content on the soil grain specific gravity, as expected. At about zero gypsum content, Gs values are consistent with those of soils, and at high gypsum content, they become closer to that of gypsum, as expected. Values of grain specific gravity have significant effects on the calculation of various soil parameters and interpretation of test results such as in the hydrometer test, soil volume-weight relationships and compaction tests. Values of Gs relevant to the percentage of gypsum crystals should be used in calculating the mentioned parameters for soils containing gypsum crystals. As with the other index properties, drying of the soil samples during determination of the Gs values was carried out at 40 °C such that properties of the gypsum crystals did not change due to dehydration at higher temperatures.

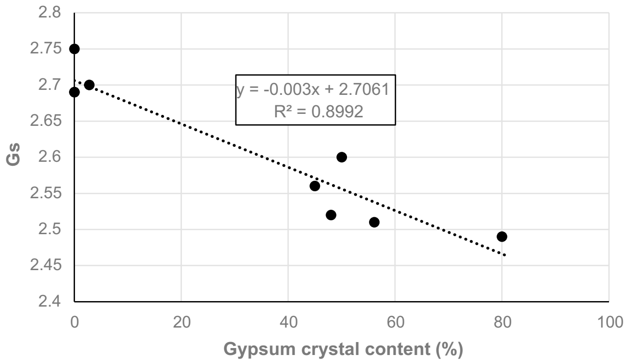


Fig. 10 Changes in the solid grains specific gravity of the site clayey soils with their gypsum crystal content

Field CBR

The California Bearing Ratio (CBR) is an important parameter used in the design of pavements, and values used in gypseous soils for this parameter should be selected carefully to avoid extra future pavement maintenance. As indicated previously, due to the fragility of the gypsum crystal grains, soils containing such grains are expected to experience higher settlements when subjected to loading. The majority of studies conducted previously on the effects of gypsum content on the CBR value involved laboratory testing aimed at determination of the effects of addition of gypsum as an agent of soil improvement and did not consider effects of presence of gypsum crystals on the in situ value of CBR. Some examples of these studies were reviewed in the introduction in "Engineering properties of gypseous soils'' section of this paper. For instance, the Kuttah and Sato (2015) studies indicated that the best soil strength performance is achieved by adding 15 to 20% gypsum to sandy soils and 20 to 25% gypsum or basanite to clayey soils. Other researchers conducted laboratory tests to examine effects of soaking, soil type, surcharge, etc. on the CBR test results in gypseous soils.

In the current study, field CBR tests were conducted according to the ASTM standard No. ASTM D4429-04 at 0.3, 0.6 and 1.0-m depths in test pits TP15 to TP18, which are a few meters away from the runway pavement. Gypsum crystals were present in clayey subsoils at some of the tested locations, but the subsoil at TP15 consisted of silty sand with no gypsum content and was, therefore, not relevant to the current study related to clayey soils containing gypsum crystals.

Figure 11 shows variations of field CBR values measured on in situ low plasticity clayey soils with the percentage of gypsum crystal content and indicates that field CBR is strongly influenced by the presence of gypsum crystals. It is noted that as indicated previously, groundwater level in the site is at great depth and the on-site shallow soils are not saturated and may be cemented and, are, therefore, stronger than their saturated counterparts. Results shown in Fig. 8 indicate that the in situ CBR values drop from approximately 40 for a gypsum crystal content of about 35% to about 10 to 15 for gypsum crystal content of about 60%, indicating a sharp decrease of CBR with gypsum crystal content. This figure also indicates that even relatively small percentages of gypsum crystals can have significant effects on decreasing the CBR. This, in fact, is an indication of a decrease in the soil stiffness and potential increase in settlements due to loading of soils containing higher percentages of gypsum crystals.

It is of interest to compare the in situ load-settlement curves of soils with and without gypsum crystals during the field CBR tests to gain some insight into their behavior. Figure 12 compares such curves for the CBR tests at the three mentioned depths in TP18 and TP17. The subsoils at the TP18 location mainly consists of low plasticity clay with thin clayey-silty sand inter-beds containing close to 50% fines. As shown in Tables 1 and 3, no gypsum crystals were observed at any depth in this test pit, and the in situ dry densities vary within the narrow range between 14.9 and 15.1 kN/m^3 at the various depths. The soil may therefore be considered being relatively uniform with depth and consisting of predominantly low-plasticity clay. At TP17, the subsoils consist of clayey sand with 36% fines at 0.3-m depth, and low plasticity sandy clay at 0.6 and 1.0-m depths with gypsum contents decreasing from approximately 68 to 55% and dry densities increasing from as low as 10.9 to 13 kN/m^3 with depth. It is noted that where percentage of fines in the clayey sand is high, soil strength and deformation behavior are expected to be controlled mainly by the clayey soils.

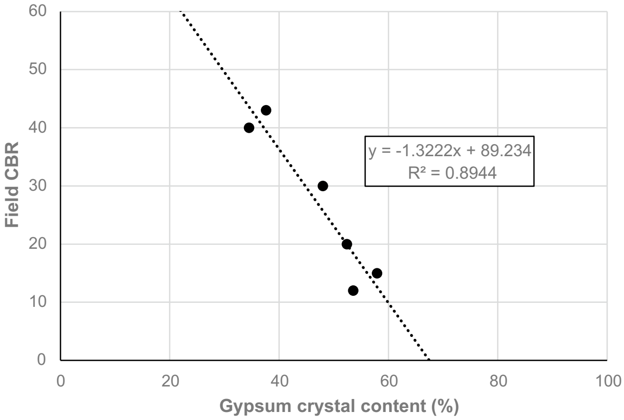
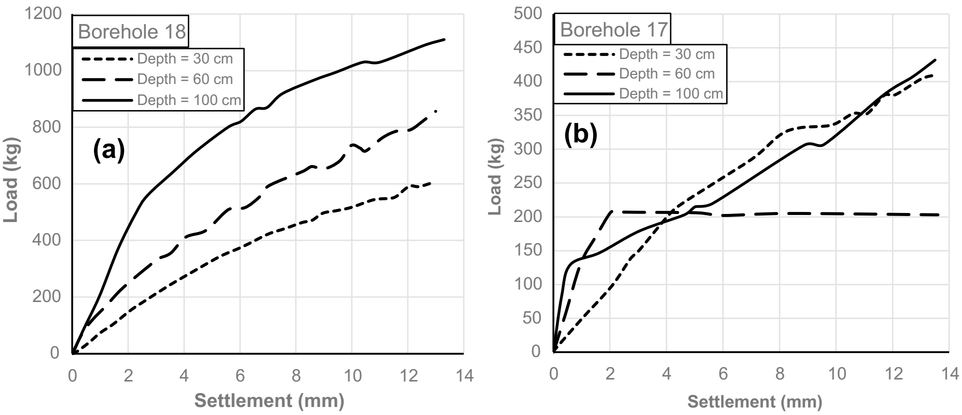


Fig. 11 Changes in the measured field CBR with the gypsum crystal content of the in situ clayey soils

Figure 12a shows the load-settlement behavior at the TP18 location at 0.3, 0.6 and 1.0-m depths during the CBR tests. A consistent increase in soil strength and stiffness with depth is observed, which is likely a result of increase in soil stiffness and/or surcharge with depth (which was applied during the field test according to the ASTM standard) in the non-gypseous soils, as expected. However, no such consistent trend is observed in the results shown in Fig. 12b for TP17, where the soil contains substantial amounts of gypsum crystals. The load-settlement curve for the test at 0.3-m depth shows monotonic increase, albeit with much smaller slope compared to its TP18 counterpart. At 0.6 and 1.0-m depths, the curve slopes are initially higher than that of the 0.3-m depth, but breaks in the slopes occur at greater loads. Compared to the results obtained at TP18, where no gypsum crystals are present, the maximum loads corresponding to the same settlements are much smaller at TP17. It is possible to interpret this behavior as being a result of breakage of the gypsum crystals after the applied loads reach certain values, although the level of load where the breaks occur and the slopes following the breaks are not the same for the two depths. These differences may be affected by the differences in the properties of the soils below the testing depth which are, unfortunately, unknown for the test conducted at 1.0-m depth.

The results described above are generally consistent with those reviewed previously in "Engineering properties of

Fig. 12 The load–settlement curves obtained from two of the CBR tests conducted at 30, 60 and 100 cm depths in the (**a**) TP18 and (**b**) TP17 test pits



gypseous soils’’ section; however, the current results involve field CBR tests on soils containing naturally formed gypsum crystals while previous studies mainly examined effects of added gypsum on soil behavior.

Compaction parameters

Compaction test results for the site clayey soils containing gypsum crystals were limited; however, the available data appears to show clear trends. Figure 13 shows maximum dry densities and OMCs obtained from the mentioned tests. Results indicate the while the maximum dry density mildly decreases with the increase in gypsum crystal content, the OMC is strongly affected and decreases with the increase in crystalized gypsum. The decrease in OMC may be considered being the result of a compaction behavior closer to granular material for the crystal grains, with little or no physiochemical interactions between the water and grains, resulting in smaller OMC. Therefore, as the crystal percentage increases, the OMC decreases similar to the effect of increase in the percentage of granular materials in a mixed sandy-clayey soil. The mild decrease in the maximum dry density despite the considerably smaller specific gravity of the crystal grains compared to the soil grains, as discussed in “Soil grain specific gravity” section, may be attributed to the possible breakage of the crystals and filling of the soil voids and the resulting decrease in void ratio in the high crystal content soils compared to the low crystal content soils.

Results reported in the literature on the effects of gypsum on the maximum dry density and OMC of soils are contradictory, with most of them reporting increase in dry density and decrease in OMC with the increase in gypsum content as indicated in “Engineering properties of gypseous soils’’ section. Many studies have also indicated that this trend is applicable up to certain percentage of added gypsum, above which the trends are reversed. As indicated before, the limited results presented in the current study indicate slight decrease in maximum dry density and considerable decrease in OMC with the increase in the natural gypsum crystal content of the low-plasticity clayey soil tested.

It is noted that in the determination of water content in the compaction tests, drying of the soil samples was done at 40 °C to avoid changing of the crystal properties since in the case of placement and compaction of soils in the field, temperatures are typically not expected to be much above this value.

Summary and conclusions

Effects of presence of gypsum crystals in a low plasticity clayey soil of an airport site were investigated based on results of in situ and laboratory tests. The crystalized gypsum content of the soil was determined using a procedure based on thermogravimetric analysis employed and verified in previous studies and also approximately checked in the current study. The gypsum content is determined by measuring water contents of soil samples containing gypsum crystals dried at 110 and 40° and using a relationship that relates the percentage of gypsum crystals to the mentioned two water contents. Plots showing variations of the various properties of the clayey soil with the percentage of gypsum crystals are presented. Results indicate that the soil in situ unit weight, water content, grains specific gravity, plasticity index, in situ CBR, maximum dry density and optimum moisture content decrease with the increase in gypsum crystal content for the low-plasticity clayey soil tested. For the soil unit weight, plasticity index, CBR and OMC, these trends obtained for naturally developed gypsum crystals are consistent with those obtained in previous studies for the effect of gypsum added for treatment of base soils. However, maximum dry density and natural water contents seem to exhibit different trends, but no previous study was found for comparison regarding the grains specific gravity, although the general trend obtained seems obvious. Load-settlement curves obtained from the CBR tests also showed weaker, irregular behavior for soils containing gypsum crystals. Considering the limited number of data for some of the correlations, further studies are recommended to examine their applicability to various conditions.

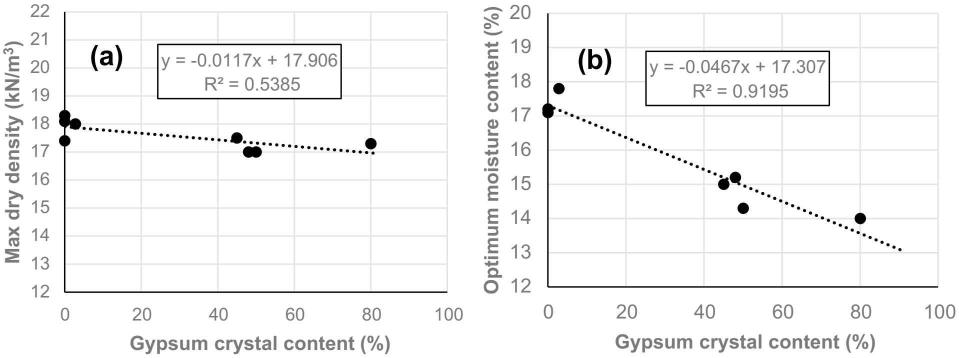


Fig. 13 Effects of gypsum crystal contents on the maximum dry density and Optimum Moisture Content (OMC) of the site clayey soils

Data Availability Relevant test data is available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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