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Geotechnical Review for Gypseous Soils: Properties and Stabilization

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ABSTRACT

In many arid and semi-arid regions, collapsible soils are well-known to be problematic in nature and negatively affect the performance of engineering structures. Gypseous soil considers one of the well-known types of collapsible soil. It represents a real challenge to engineers due to different problems encountered by engineering projects implemented in this soil. The mineralogy, composition, and fabric of gypseous soil affect its ability to deform when subjected to wetting (due to changing the whole structure soil particles). Numerous studies considered the problems of gypseous soils and their treatment with different additives and using different methods. In this paper, the properties of gypsum (physical appearances, hardness, density, chemical structure), gypsum effect on soil properties (specific gravity, compaction properties, shear strength), main geotechnical properties of gypseous soils, their problems, and different important additives (traditional and non-traditional) and methods used in gypseous soils problems mitigation have been discussed. Gypsum is one of unpredictable materials that have different forms, low hardness, and low density. Gypsum is the main occurring source of sulphate in soils, it affects their geotechnical properties to different degrees depending on its content, the presence of the other salts (than gypsum), soil gradation and type, and organic matters. There is a critical gypsum content beyond which gypsum negatively affects the shear strength of soils, this content is (10-20)%. Finally, although there are many additives used in the treatment of gypsum soil, the use of some additives should be done with caution to avoid destructive results, especially with clay gypseous soil.

Keywords: Gypseous soils; Collapse; Stabilization; Wetting and soaking; Soil improvement

INTRODUCTION

Many soils have been characterized as problematic soils in geotechnical engineering. Some of these soils may collapse, expand, undergo excessive settlement, or disperse. Other problematic soils may have soluble or have a distinct lack of strength. There are many reasons for the problematic nature of soils, like the mineralogy of the soils, soils composition, soils fabric, and the fluid in the soil pores (Husain et al. 2018; Al-Taie et al. 2020; Al-Baidhani & Al-Taie 2021). Collapsible soils are among the most problematic soil types. Many studies have focused on these soils because of their problems from an engineering point of view. When wet, collapsible soils have a high ability to deform as a result of the entire structure of their particles changing. The regions that have arid and semi-arid conditions are the regions of deposition of collapsible soils. Large distress to engineering structures and severe damages may result from the failure of collapsible soils (Al-Busoda 2008; Moret-Fernández & Herrero 2015; Al-Baidhani & Al-Taie 2020).

Gypseous soil is a well-known type of collapsed soil that may be found in many places throughout the world, including Russia, Australia, Spain, and Argentina. In Iraq, there are considerable areas in which the soils were classified as gypseous soil (Porta 1998; Khademi-Moghari 1998; Aznar et al. 2013; Sa'eb et al. 2017). According to Boyadgiev (1974) and FAO (1990), about 9% of the whole global gypseous soils are lying in Iraq. Nashat (1990) stated that gypseous soil constitutes 20% or more of the area of Iraq. There are several types of gypseous soil that will be mentioned later in this paper (Fattah et al. 2014). Engineers face a real challenge when working with gypseous soils because of the different issues that arise during the implementation of engineering projects in or on these soils. The continuous dissolution of gypsum-forming gypseous soils is the main reason for such problems. Since the continuous flow of water through the soil works to dissolve the gypsum, and since gypsum acts as a cement bonding material for soil particles, the wetting of the soil, immersion with water, or the flow of water through the soil's porous weaken the gypsum, or removes it by the action of dissolution and thus exposes the soil to undesirable collapse and settlement (Saoudi et al. 2013; Aldaood et al. 2015; Al-Taie et al. 2020).

Several studies focused on the challenges with gypseous soils and how to treat them with different additives and techniques. Lime and cement are, the classic soils' stabilizers, have been used in the stabilization of gypseous

soils. Emulsion asphalt, fuel oil (refinery waste), crude oil, and cut-back bitumen have also been investigated as a waterproofing, mitigation, and stabilizer for gypseous soils. The protection of gypseous soil and trying to reduce water access to it, by using a layer of impermeable soil (with an appropriate thickness) to be placed under the foundations, is one of the methods used to reduce the problems of gypsum soil (Al-Zory 1993; Al-Alawee 2001; Esho 2004; Aziz & Ma 2011; Jha & Sivapullaiah 2017; Al-Hadidi & Al-Maamori 2019).

In this review paper, the properties of gypsum, its effect on clay and sand soil properties, the main geotechnical properties of gypseous soils and their problems, and different important additives (traditional and non-traditional) and methods used in gypseous soils problems mitigation have been reviewed and discussed. The effect of gypsum as a stabilizer or destabilizer agent has been shown and the critical gypsum content has been determined based on the reviewed papers.

GYPSUM PROPERTIES AND GYPSEOUS SOILS

The chemical composition of the gypsum consists of layers of $(SO_4)^{+2}$, $(Ca)^{+2}$ ion, and sheets of water ((H_2O) molecules). The sheets of water separate the groups of $(SO_4)^{+2}$ and calcium ions as shown in Figure 1. Weak bonds exist between the water molecules in the neighboring sheets (Yu et al. 2016).

The gypsum reveals different physical appearances, it may be found in different colors and shades based on the type and amount of impurities. It may be colorless, red-brown, white, or grey. According to the Mohs scale, the hardness of gypsum is low. The solid particles of gypsum have relatively low density (approximately 2.3) (Mohammed & Mahmood 2018).

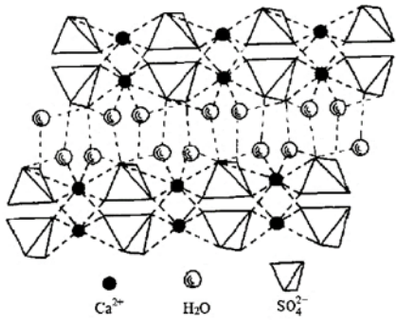


FIGURE 1. Crystal structure model of original gypsum (Chen 2006)

There are different forms of gypsum, these are calcium-sulphate hemihydrate ($CaSO_4$- $0.5H_2O$), sulphate dihydrate ($CaSO_4 2H_2O$), and calcium sulphate anhydrite ($CaSO_4$. H_2O). The percentages of calcium oxide (CaO), sulphur trioxide (SO_3), and water (H_2O) in gypsum are 32.6%, 46.5%, and 20.9%, respectively. The chemical structure of gypsum may change at a temperature above 60 ℃ and with the presence of water, due to this property, gypsum has been considered as one of the most unpredictable materials (Yılmaz 2001; Solis & Zhang 2008; Kuttah & Sato 2015).

The dehydration of gypsum, $CaSO_4$ $2H_2O$, between (0 - 65) °C losses the first one and a half molecules of water, leading to the formation of bassanite or hemihydrate, $CaSO_4.1/2H_2O$ as shown in equation 1

$$CaSO_4\ 2H_2O \rightarrow CaSO_4.1/2\ H_2O \quad (1)$$

Half of the water molecule of bassanite continue to exist relatively stronger (up to a temperature of 70 °C), with a further temperature (about 95 °C), bassanite losses half the water molecule, as a result, it converts to anhydrite, $CaSO_4$ as shown in equation 2

$$CaSO_4.1/2\ H_2O \rightarrow CaSO_4 + 1/2\ H_2O \quad (2)$$

With the presence of water, anhydrite and hemihydrate again convert into gypsum as shown in equation 3 and Figure 2 (Herrero & Porta, 2000; Claisse & Ganjian, 2006; Solis & Zhang, 2008; Zedan & Abbas, 2020). The following represents gypsum phase transformation (Jha & Sivapullaiah, 2014).

$$CaSO_4. + 2H_2O \rightarrow CaSO_4\ 2\ H_2O \quad (3)$$

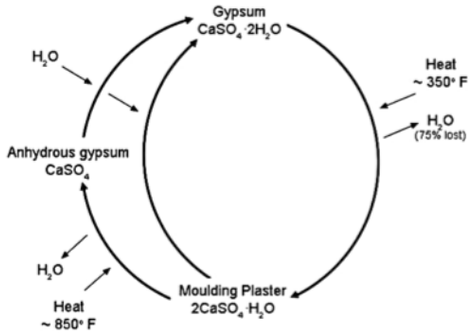


FIGURE 2. The cycles of gypsum (Jha & Sivapullaiah, 2014)

Gypseous soils have a variety of origins and definitions. According to the literature, the soils can be classified as gypseous based on the content of gypsum. Different researchers stated that the soils with more than 40% gypsum can be classified as "gypseous", while soils with gypsum content of 1% to 40% have been termed as "gypsiferous soil" (Boyadgiev & Verheye, 1996; Eswaran & Zi-Tong, 1991; Herrero Isern, 2004; Aznar et al. 2013; Pearson et al. 2015; Warren, 2016). Authors like Barazanji (1973) used subgroups to descript the texture of soils containing gypsum. He used the term " gypsiferous " to descript soils with gypsum content of 0.3% to 50%, while the subgroups used by this author were based on the content of gypsum as shown in Table 1. The subgroups or subdivisions used are " non-gypsiferous", "very slightly gypsiferous", " slightly gypsiferous", " moderately gypsiferous", "highly gypsiferous", and "very highly gypsiferous". As shown, the suitable terminology to denote the gypsum-containing soils is still a debatable issue.

Another classification of these soils is shown in Table 2. It's based on many soil properties (in addition to the content of gypsum). The soils have been classified either as " gypsiferous soil" or " highly gypsiferous soil" based on their gypsum content. Soils that are classified as " gypsiferous" have their physical, engineering, and chemical properties that distinguished these soils from highly gypsiferous soils. In this classification, attention is given to soil plasticity and its relation to soil grain size, also, the relation between the total dissolved solids, soil voids, and soil collapsibility are included. The effect of basic soil properties (e.g. water content, Atterberg limits, soil grain size) on the collapsibility is included in the proposed classification. Moreover, the relation between shear strength parameters of soils and their density grain size, and gypsum content is, also included (Al-Dabbas et al. 2012).

TABLE 1. Classification of gypseous soil according to gypsum content (Barazanji 1973)

Gypsum content %	Classification
0.0 – 0.3	Non – gypsiferous
0.3 – 3	Very slightly gypsiferous
3 – 10	Slightly gypsiferous
10 – 25	Moderately gypsiferous
25 – 50	Highly gypsiferous
>50	very highly gypsiferous

TABLE 2. Classification of gypsiferous soils based on different properties (Al-Dabbas et al. 2012)

Gypsum (%)	0.5 to 25	25 to ≥50
Classification	Gypsiferous soil	Highly gypsiferous soil
Initial void ratio	<0.45	>0.45
Coeff. of curvature	<2.5	>2.5
Uniformity coeff.	<25	>25
Collapse potential (%)	<1.5	>1.5
Comp. strength (MN/m^2)	<1	>1
Cohesion (kN/m^2)	<15	>15
Plasticity Index (%)	<10	>10
Fine-grained soils (%)	<50	>50
TDS of soil water extracts (ppm)	<350	>350

GYPSUM IN SOILS

Sulphate minerals in soil have several sources. These are either primary (or direct) sources and secondary sources. In primary sources, sulphate is present in natural form like gypsum. These sources represent the sulphate-bearing mineral. Magnesium sulphate, sodium sulphate, and calcium sulphate are established as primary sources. However, the main occurring source of sulphate in soils is gypsum. While in secondary sources, the sulphate is present as a byproduct of oxidation or other forms of chemical interactions.

The formation of gypsum has different ways. These are the precipitation of ions like sulphate (SO_4^{-2}) and calcium (Ca^{+2}) on soils (from rain), and the transformation of sulphur - rich minerals (e.g. pyrite) into sulphuric acid. In the first one, the formed gypsum is lenticular gypsum. While in the second one, the transformation of sulphur-rich minerals is conducted with weathering and oxidation processes, sulphuric acid reacts with calcium (in the presence of water carbonate in the calcareous soil) and this forms gypsum as shown below:

$$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4.2H_2O + CO_2 \quad (4)$$

The sulphate concertation in the soils may increase as a result of the dissolution process of the sulphate from the topsoil layer. This leads to entering the dissolved sulphate into the pavement layers, and, due to evaporation, this causes a moving of the sulphate in the upper direction. As a result of these processes, pavement failure occurs. Hence, transported of sulphate (by water) is an instance of a secondary source of contamination of sulphate (Dermatas 1995; Rollings et al. 1999; Li et al. 2020). The irrigation water (with high content of calcium ion and sulphate ion) may assist in gypsum formation. The replacement of sodium chloride by calcium sulphate is occur when a substantial content of sulphate and calcium ions are present in the irrigation water. Since sodium chloride is much more soluble than calcium sulphate, gypsum can be formed from the partial leaching of salt from the soils.

There are many uses and applications of gypsum, as a construction material in construction projects (in form of plasterboard), to improve the properties of subgrade soils, to maintain the power of hydrogen "pH" of soil for agricultural purpose, and for industrial purposes. Annually, millions of tons of gypsum are used in different applications in the world. As a result of its uses and applications, gypsum may introduce to soils indirectly to form what is termed as ''artificially induced gypseous soil'' (Fisher 2011; Kuttah & Sato 2015).

EFFECT OF GYPSUM ON SOIL PROPERTIES

The geotechnical properties of soils are highly affected by the content of gypsum. Gypsum influences both the physical properties (e.g. specific gravity, compaction parameters), and engineering properties (e.g. shear strength parameters, and soil compressibility and collapsibility) of soils. A thorough investigation of the gypsum effect on soil properties is an important and critical issue. This is due to gypsum significant effect on soil bearing capacity and, as a result, the stability of the structures found on the soil. In the following sections, the mentioned effects of gypsum have been presented and discussed according to the literature.

EFFECT OF GYPSUM CONTENT ON SPECIFIC WEIGHT OF THE SOIL

The presence of gypsum has a significant effect on the specific gravity of soils. According to literature, the soils with gypsum have a lower specific gravity in comparison to those without gypsum. When the gypsum content increases, the specific weight of soils decreases. Figures 3 and 4 show the effect of gypsum content on the specific weight of different soils. The data have been compiled from different works of literature (Al-Numani, 2010; Karim et al. 2013; Aldaood et al. 2014;Kadhim, 2014; Nasir & Schanz, 2017; Husain et al. 2019;Mohammed et al. 2019; Al-Hadidi & Al-Maamori, 2019; Al-Adhamii et al.2020; Al-Murshedi et al. 2020; Al-Obaidi et al. 2020; Zedan & Abbas, 2020) and plotted in Figures 3 and 4. Based on compiled data, it can be seen that the specific gravity of gypseous soils may range from 2.28 to 2.61 (Nusier et al. 2008). In general, granular gypseous soils, without fines or with 5% or fewer fines, are classified as "poorly graded or SP" according to unified classification (ASTM D 2487) Such soils showed higher specific weight than granular gypseous soils containing more fines (i.e. silt or clay materials). In other words, the specific gravity of gypseous soils is affected by the classification of the soil and the amount of available gypsum.

In Figure 4, the linear trend was adopted to represent the effect of gypsum content on the soil-specific gravity. As shown, the specific weight of soils is inversely proportional to the content of gypsum. Ahmed (2013) found that mixing sandy soil (which has a Gs value of 2.65) with different content of gypsum leads to decreasing the Gs value of the mixture. This reduction has been attributed to a lower specific gravity value of gypsum, 2.33. The specific gravity, is also, affected by factors like soil gradation (the content of clay, silt, sand, and gravel), the content of organic matters, the presence of other salts than gypsum, etc. (Al-Abdullah 1995; Al-Dabbas et al. 2012).

EFFECT OF GYPSUM CONTENT ON SOIL COMPACTION CHARACTERISTICS

Gypsum has different effects on the compaction properties of soils. These effects depend on many factors as presented in the literature. Ahmed (2013) conducted standard Proctor compaction to test sandy gypseous soils with different gypsum content (from 0% to 80%, with 10% increment). He evaluated the effect of different amounts of gypsum on the compaction properties of sandy gypseous soil. It was found that, with less than 30% gypsum content, the unit weight and optimum water content of soil were slightly affected, the first is increased while the last decreased.

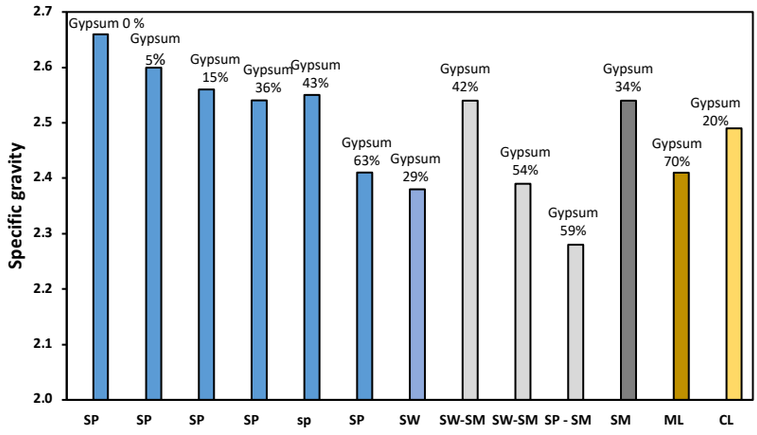


FIGURE 3. The variation of specific gravity for different gypseous

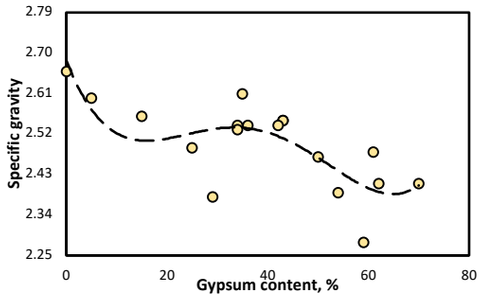


FIGURE 4. Effect of gypsum content on specific gravity of gypseous soils

This was noted for soil with gypsum content up to 15%. For further increase in gypsum content, a significant effect has been denoted. With gypsum content greater than 30%, the dry unit weight of sandy gypseous soil was decreased while the optimum water content increased noticeably. The mentioned behavior in compaction properties of sandy gypseous soil has been attributed to the fowling:

1. The effect of gypsum as a filling material in the soil matrix, the intergranular soil's voids fill with gypsum.
2. Due to the low specific gravity of gypsum in comparison to the sandy soil, as a result, with a further increase in the amount of gypsum, the overall specific weight of the mixture decreases.

Compaction behavior in clay gypseous soil is influenced by factors other than the specific weight of gypsum. It depends on the grain size of the gypsum as a material. The presence of finer grain gypsum (less than 0.355 mm) with sandy silty clay causes a decrease in the maximum soil unit weight and an increase in the optimum water content. While gypsum grains with sizes between 0.85mm and 1mm cause a decrease in both compaction soil parameters. According to the literature, the following reasons explain the reduction in compaction properties of cohesive gypseous soil (Subhi, 1988):

1. With clay particles, gypsum can produce cementation bonds. Some compaction efforts dissipate in order to break these bonds, resulting in a drop in compaction unit weight.
2. The compaction of gypsum and clay may involve" cation exchange". This may also lead to reducing the plasticity of clay gypseous soil, forming agglomeration and flocculation of the soil, decreasing the surface area, increasing the edge to the face of the particles' contact, and as a result, reducing the optimum water content.

The mentioned behavior may be affected by the initial consistency of clay soil. In soft clay, it was noticed that increasing the content of mixed bassanite (hemihydrate, $CaSO_4.0.5H_2O$) with soft clay causes an increase in soil's unit weight and a decrease in soil's water content. The potential of $CaSO_4.0.5H_2O$ to absorb the water causes an increase in the unit weight of the soft clay samples. This increase in unit weight is directly proportional to the content of the bassanite. On the other hand, the mixing of bassanite with soft clay may develop hardening between the particles of soil, and this can reduce or prevent the water from penetration inside the soil samples, and as a result, no more absorption of water by the soil. According to the literature, the compaction characteristics of gypseous soils have been compiled to present the typical value or range for maximum unit weight and optimum water content of these soils. As shown in Figure 5, the typical ranges for maximum unit weight and optimum water content of gypseous soils are

(13.9 kN/m^3 to 18.8 kN/m^3) and (11% to 18%), respectively. The relation between the gypsum content and the maximum unit weight of the compacted gypseous soils is shown in Figure 6. It is clear that there is an inverse relationship between the gypsum content and the maximum unit weight of gypseous soils. This is due to the reasons discussed early in this section. The same relation can be seen for the effect of gypsum on the optimum water content of the soil, except for very low gypsum content (<5%) (Al-Numani 2010; Kamei et al. 2012; Aldaood et al. 2014; Kadhim 2014; Nasir & Schanz 2017; Husain et al. 2019; Al-Hadidi & Al-Maamori 2019; Mohammed et al. 2019; Al-Adhamii et al. 2020).

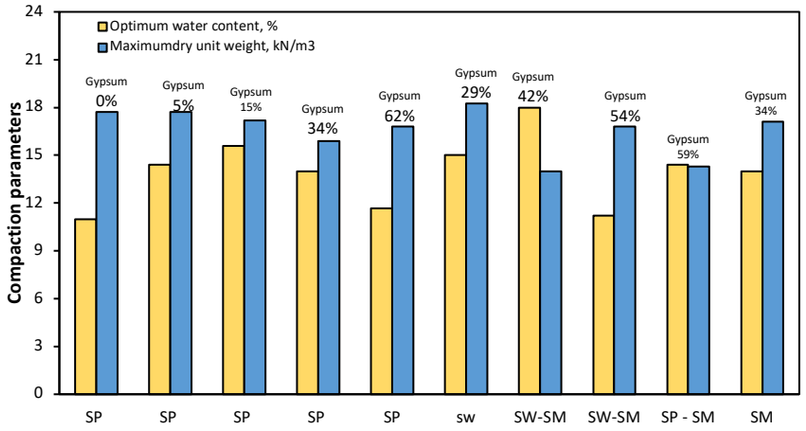
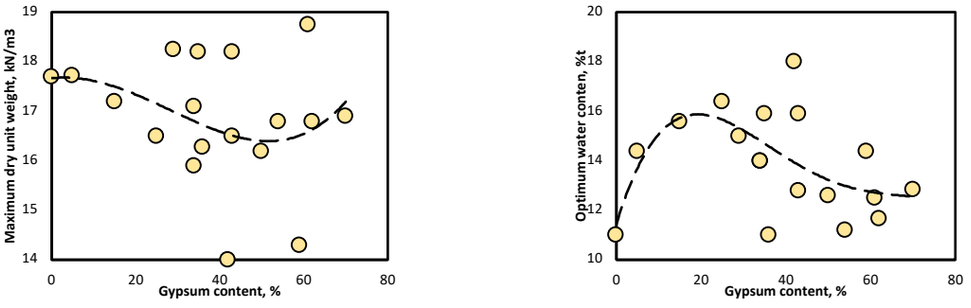


FIGURE 5. The variation of compaction characteristics of different gypseous soils



a b

FIGURE 6. Effect of gypsum content on a: maximum dry unit weight; b: optimum water content of gypseous soils

EFFECT OF GYPSUM CONTENT ON SOIL STRENGTH

In geotechnical design, the shear strength parameters of soils are very important, especially in the bearing capacity determination. The presence of specific content of gypsum in soil composition represents a critical issue from a geotechnical point of view. The shear strength parameters of the soils are highly affected by the presence of gypsum, especially when these soils expose to wetting and drying. In turn. the amount of gypsum in the soil is affected by the soaking period and the magnitude of the confining water pressure (Salih & Mohammed 2017; Mohammed & Salih 2018).

There are numerous researches directed to explore the effect of gypsum content on shear strength parameters of the soil. The undrained shear strength of silty clay soil with different contents of gypsum (from 0% to 10%) has been studied for unsoaked samples tested under unconfined conditions. It was proven that there is a direct relationship between the strength of silty clay and the content of gypsum (within the investigated gypsum content, i.e. 0% to 10%) (Ramiah 1982). The bearing ratio values of the silty clay soil are affected by the content of gypsum percent in the soil. There is an upper limit of gypsum content at which the CBR of the soil (under soaked condition) increases (for gypsum content below this limit), then the bearing ratio values reduce for further increase in the gypsum content. As stated in the literature, the upper limit is 15% (Al-Ani et al. 1991). The shear strength parameters of clay gypseous soil are affected by the content of gypsum. Clay soils with gypsum content less than 15% show a significant increase in cohesion component, this increase is proportional to the content of gypsum. Below this content, the presence of gypsum reduces the porosity due to the formation of crystals in the soil's pores, as a result, the cohesion of clay increases (Petrukhin & Arakelyan 1985). For cohesive silty soil, adding 0% to 15% of gypsum (in form of bassanite) leads to improving the compressive strength to more than six-folds (Kobayashi et al. 2013). With a further increase in gypsum content (greater than 15%), there is a critical value of cohesion is reached. Beyond this value, the cohesion

of clay reduces. This behavior is caused by the failure of crystal bonds to form (Petrukhin & Arakelyan 1985).

The gypsum content has an important effect on the angle of the internal friction of the soils. For clay gypseous soil of low plasticity, the internal friction is directly proportional to the gypsum content (Salas et al. 1975). For sandy loam gypseous soil, the internal friction increases with increasing gypsum content, this is, however, accepted for soil with gypsum content less than or equal to 25%. With a further increase in gypsum content (>25%), the internal friction value of sandy loam gypseous soil decreases. This behavior has been attributed to an increase in mineral friction as a result of raising the amount of gypsum in the soil to a certain level (25 percent). While increasing the porosity of the soil leads to a reduction in internal friction, the opposite effect of gypsum has been attributed to increasing the porosity of the soil (Petrukhin & Arakelyan 1985). The role of gypsum in strength development of clay soils is important for samples subjected to cycles of freezing and thawing. The strength of clay soils mixed with gypsum, in form of bassanite, is improved with increasing the gypsum content (up to 20% gypsum). The resistance of clay soil samples to cycles of freezing and thawing is affected by the content of bassanite, in fact, the best resistance is reached at 20% bassanite (Kamei et al. 2012).

On the other hand, the effect of gypsum on strength parameters of the soils is dependent, to some extent, on soil type. The significance of the gypsum presence is different in cohesive soils than cohesionless type, it is more significant in the last soils (Kobayashi et al. 2013). Adding 0% to 20% of gypsum (recycled) to poorly graded sand can improve the shear strength of the stabilized soil. The role of gypsum in the cementation (hardening) of soil particles has been attributed to this improvement. As a result, the cohesion strength between these particles improves, as does the shear strength (Ahmed & Ugai 2011). The development of cohesion in granular gypseous soils is highly affected by the presence of water. Examination of the effect of soaking of granular gypseous soils has been investigated and discussed in this review. Data from different literature (Karim et al. 2013; Al-Adhamii et al. 2020; Al-Murshedi et al. 2020; Al-Obaidi et al. 2020; Zedan & Abbas 2020) have been collected and plotted in Figure 7. It can be noted that the cohesion of gypseous soils is highly affected by soaking at which a considerable reduction in cohesion values appears for soaked gypseous soils. Furthermore, for the same soil group, the reduction in cohesion due to soaking is directly proportional to gypsum content. The effect of soaking on gypseous soils with fines (silt and clay) is more significant in comparison to soils with little fines (like poorly graded soil, SP).

The effect of soaking on the internal friction for different granular gypseous soils has been included in this review. Data from literature (Karim et al. 2013; Al-Adhamii et al. 2020; Al-Murshedi et al. 2020; Al-Obaidi et al. 2020; Zedan & Abbas 2020) has been collected and plotted as shown in Figure 8. Internal friction values collected for granular gypseous soils with various particles represent soaked and unsoaked conditions (silt and clay). It is clear that regardless of the group of soils, the internal friction of dry and soaked gypseous soils increases with the increase in the content of gypsum. The internal friction values are affected by wetting, they are reduced as the soils are soaked in water. The soils with higher fine content are highly affected by soaking, and soils with fine materials less than 5% (i.e. SP) show less reduction in friction in comparison with silty sand, SM, soils, while the minimum effect of soaking on internal friction values can be noted for the well-graded gypseous soils which have (5% to 12%) fine content (i.e. SW-SM).

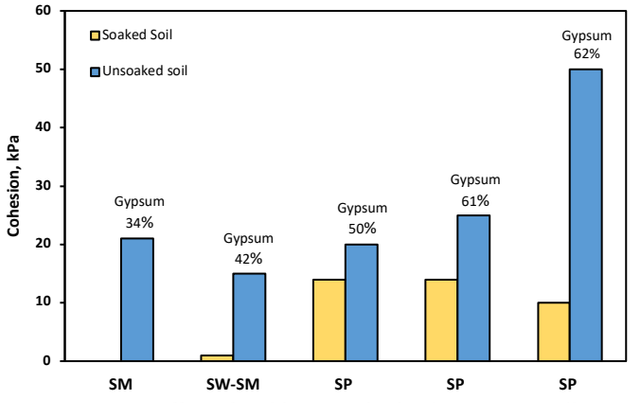


FIGURE 7. Effect of soaking on cohesion in gypseous soils

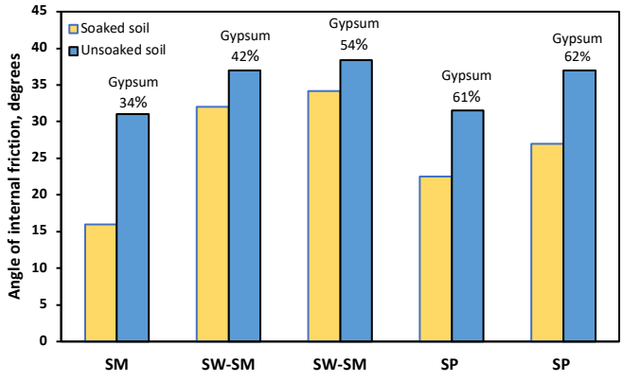


FIGURE 8. Effect of soaking on internal friction in gypseous soils

STABILIZATION OF GYPSEOUS SOILS

The presence of gypsum in soil composition makes the soil one of the more complex materials that challenge the geotechnical engineer. Due to the possibility of encountering the gypseous soils in many regions, it is very essential to study, in detail, the engineering properties and behavior of these soil. The engineering behavior of soils is highly affected by the presence of gypsum. This effect is dependent on factors like the content of gypsum, the type of soil, and the degree of hydration of gypsum. All over the world, there is interest in studying gypseous soils. In fact, there is a complexity in the behavior of these soils. In some cases, such complexity led to a contradiction in the results of some research programs. Despite this, the researchers agree that gypseous soils should be stabilized and improved before they can be used in geotechnical applications. The negative effects of gypsum on soil properties can be mitigated using different methods, some of these methods are summarized in this review. However, the selection of the reveal stabilization method for problematic soils is depending on factors like the conditions of the site, the cost of application, the availability of the additive materials, the design requirements, and environmental aspects (Albusoda & Khdeir 2018; Al-Naje et al. 2020, 2021)

STABILIZATION OF GYPSEOUS SOILS WITH MECHANICAL METHODS

In physical stabilization, mechanical methods (e.g. compaction, replacement, reinforcement, etc.) are used to improve the properties of soils. Compaction is widely used in almost all civil engineering projects. In general, the permeability of soil is decreased when the soil is compacted. In gypseous soils, the dissolution of gypsum is highly affected by the permeability of the soil, hence, the compaction is important in the case of gypseous soils. The effect of compaction effort on the bearing values of gypseous soil has been studied by different researchers. The chemically stabilized clay gypseous soil (with a gypsum content of 33%) has been subjected to different compaction efforts (Razouki & Kuttah 2004, 2006; Razouki et al. 2011; Razouki et al. 2012). It was found that the increase in the number of blows per compacted layer, from 12 blows to 56 blows, improved the bearing ratio values by more than 6 folds. It was reported that both the soaked and unsoaked gypseous soil are improved as the compaction effort increased. The effect of compaction on the bearing values is more pronounced as the period of soaking in water increases. It should be mentioned that the response of gypseous soils to changes in compaction effort depends on the amount of gypsum presence in the soil composition. Furthermore, the compressibility of the gypseous soils depends on the applied compaction effort. As the soil is compacted with higher effort, its compressibility and collapsibility decrease. This is due to the improvement in the value of the compression index and the collapse potential of compacted and soaked soil. However, the compressibility of gypseous soils is highly affected by the gypsum content (Al-Zubaidy et al. 2022).

Authors conducted experimental tests (including compaction, compressibility, and collapsibility tests) on gypseous soil with varying amounts of gypsum and tested them under different compaction efforts. They were found that the improvement in soil compressibility is related to the number of blows and dropping height applied in the compaction process. The compression index values decreased as these parameters were increased. They also found that as the amount of gypsum in the soil increases, the effect of compaction on compressibility improves. Compaction, on the other hand, reduced the effect of soaking on the gypseous soils' collapsibility (Abid Awn et al. 2012; Al-Taie & Al-Shakarchi 2016; Hussein 2018).

Replacement of highly gypseous soil with other cohesive or cohesionless soils (non-gypseous soils) is also used as a physical stabilization method. This method aims to reduce the effect of high gypsum content on the behavior of soils. Replacing 5% to 15% of gypseous soils with silty sand soil or silt soil can considerably mitigate the collapsibility of gypseous soils. While, the compression index of gypseous soil might not show any improvement at these ranges of replacements (Zbar & Hessain 2013; Najah et al. 2013; Albusoda & Hussein 2013)

Reinforcement of gypseous soils using different materials (e.g. strips of different materials, geosynthetics, geotextile, etc.) can help in reducing some negative properties of these soils. Using strips made of different materials as

a reinforcement to gypseous soils may reduce the collapse potential of the soil. Materials like stainless steel, plastic grid, mats of reed, nylon, etc. can be used to produce the strip of reinforcement. Experimental investigations showed that the best improvement can be obtained using a strip of the plastic grid as a reinforcement to gypseous soils (Abid Awn 2004). Placing geogrid, single layer or double layers, at different depths in gypseous soils can positively affect the shear failure mode and bearing capacity values. In this case, the location of geogrid is important to reach the optimum improvement in bearing capacity values and to reduce the settlement of gypseous soil. To achieve the required improvement, the geogrid should be placed at a depth equal to the width of the footing. On the other hand, increasing the number of reinforcement layers within this depth is the most important to ensure an effective reduction in collapse settlement and increase the bearing capacity values. The maximum improvement in bearing capacity of soils, as stated in the literature, has been recorded using four layers placed at a distance of 0.25 of a width of footing (Ranadive & Jadhav 2004; Soliman & Hanna 2010; Karim et al. 2017).

Finally, a combination of more than physical stabilization methods may produce more improvement in the bearing capacity and settlement of gypseous soils. Replacing some of the gypseous soil with more stable soil (like fine clean sand) and reinforcing the interface between the soils' layers can mitigate more than 60% of the collapsibility of the gypseous soil (Albusoda & Hussein 2013).

STABILIZATION OF GYPSEOUS SOILS WITH CHEMICAL METHODS

In chemical stabilization, additives from different sources are used to improve the properties of problematic soils (Al-Kalili et al. 2021; Hussein et al. 2021). With respect to collapsible soils (including gypseous soils), the following groups of additives have been used in research as chemical agents (Ferris et al. 1991; Harris et al. 2005; Aldaood et al. 2014; Iranpour & Haddad, 2016; Albusoda & Khdeir, 2018; Snodi & Hussein, 2019; Aldaood et al. 2021; Al-Naje et al. 2021):

1. The group of traditional additives like cement, lime, bituminous, and emulsified asphalt
2. The group of salts additives like chloride salts, calcium chloride (in form of dihydrate), barium chloride, ammonium carbonate, ammonium oxalate. barium hydroxide.
3. The group of industrial and domestic wastes includes silica fume, fly ash, tire rubber waste, rice husk ash, ceramic, ground-granulated blast, and glass.
4. The group of nanomaterials e.g. nano coal fly, nano ash, nano-silica fume, nano-clay, nano-copper, nano-alumina, and nano-silica.

The use of reveal chemical stabilizer depends on many factors like design condition, site conditions, and economic factors. Also, the determination of the proper amount of the chemical additive varied widely in the literature. It depends on soil type, gypsum content, and type of stabilizer. However, there are limitations to using some types of chemical additives to stabilize the clay gypseous soils. Chemical additives that contain calcium in their composition should be used with caution. The use of such additives may lead to devastating results (Harris et al. 2005). Researchers (Harris et al. 2005; Nair & Little 2009) recorded some damages for soils treated with such type of additives. They mentioned that special attention should be given to the cases of soil damages. These damages have been attributed to the formation of expansive minerals with an ability to water absorption and volumetric expansion (Nair & Little 2011).

In this paper, the effect of different chemical stabilizers on the properties of gypseous soils has been reviewed and discussed. The physical properties of gypseous soils were found to affect by adding different additives. The response of soil properties is varied from one additive to other. For instance, the "polymer" and "copolymer" materials cause an increase in the compaction properties of gypseous soil. The effect of these materials on optimum water content is higher than that on maximum dry density, also, the effect of "polymer" is higher than that of "copolymer". However, a low content of these additives (about 3%) is sufficient to reach the maximum effect (Mohammed et al. 2019).

Some additives, such as silicone oil, have a lubricating effect that helps improve the density of compacted gypseous soils. In fact, because silicone oil has a higher lubricating effect than water, adding it to gypseous soils reduces voids by rolling lubricated soil particles over each other and filling soil voids with lubricated particles. This, in turn, causes an increase in soil density and makes the change in the void ratio of treated soil is less under loading conditions (Al-Obaidi 2014; Nasir & Schanz 2017).

The nanomaterials (like nano-silica fume) have their effect on the compaction characteristics of the gypseous soils. They cause a considerable increase in maximum density and optimum water content. It has been proven that the addition of 4% nano-silica fume increases the density by about 40% and water content by 66%. The high surface area of nanomaterials has been related to the rise in compaction water content of gypseous soil treated with these materials (Albusoda & Khdeir, 2018; Al-Murshedi et al. 2020; Al-Obaidi et al. 2020).

A comparison between the effect of different additives on the compaction properties of gypseous soils has been conducted in this review. Data from the literature have been compiled and plotted in one figure as shown in Figure 9. It is clear that the effect of different additives is varied widely, where the maximum increase in soil density is attained by using nanomaterials as stabilizers, while the minimum increase in soil density is noted for polymer materials. Also, the mixing of cement and ceramic materials together shows better efficiency as soil stabilizers. Re-examination of Figure 9 shows that the change in optimum compaction water content depends on the stabilizer used, some additives (like cement, ceramic, and silicon oil) cause a reduction in water content, while some of them (like polymers, and

nanomaterials) cause an increase in water content (AL-Numani 2010; Nasir & Schanz 2017; Mohammed et al. 2019; Al-Murshedi et al. 2020).

The effect of different stabilizers on the collapsibility of gypseous soils has been reviewed in this paper. The collapse of gypseous soils, as determined from the oedometer test (single collapse test and double oedometer test) or from the experimental physical model test, is resulted from destroying the cementation bonds between soil particles upon saturation condition. As a result of this process, the soil particles are rearrangement and a new state of equilibrium is reached. In fact, the compressibility increases as a result of the collapsibility of gypseous soils. The adding of chemical additives to gypseous soils can mitigate the negative effects of collapsibility due to reducing the collapse potential of the soil.

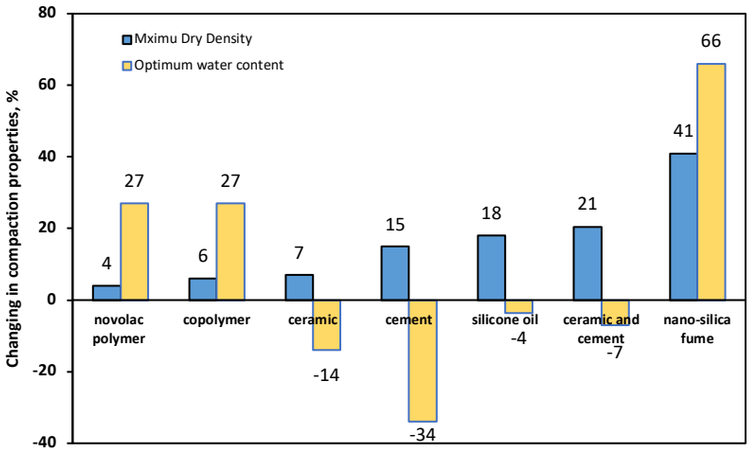


FIGURE 9. Effect of some additives on compaction properties of gypseous soils

A comparison between the effect of different additives on the collapsibility properties of gypseous soils has been conducted in this review. Data from the literature have been compiled. The compiled data has been used to calculate "the collapsibility reduction factor, CRF". This factor is used to compare the collapse potential of the soil after and before treatment with stabilizers, and calculates from the following formula:

$$CRF = 1 - \frac{CP_t}{CP_n} \times 100$$

Where CP_t is the collapse potential of treated soil, and CP_n is the collapse potential of untreated soil. Figure 10 shows the variation of the calculated CRF with different additives from different literature. The additives shown in this figure are novolac-polymer, co-polymer polymers, fly ash- polyester mixture, nano-silica fume, silicone oil, crude oil, clinker, calcium chloride, cement, lime, and kaoline (Al-Neami 2010; Ibrahim et al. 2016; Nasir & Schanz 2017; Mohammed et al. 2019; Al-Hadidi & Al-Maamori 2019; Al-Murshedi et al. 2020; Al-Obaidi et al. 2020). It is clear that the effect of different additives is varied widely, where the best increase in CRF (CRF>80%) has been obtained by using nano-silica fume, or traditional additives like cement or lime, while low CRF values (<50%) have been obtained when polymers or silicon oil additives used. Also, it could be seen that mixing the polymers with waste materials like fly ash improves the efficiency of additive and increase CRF value.

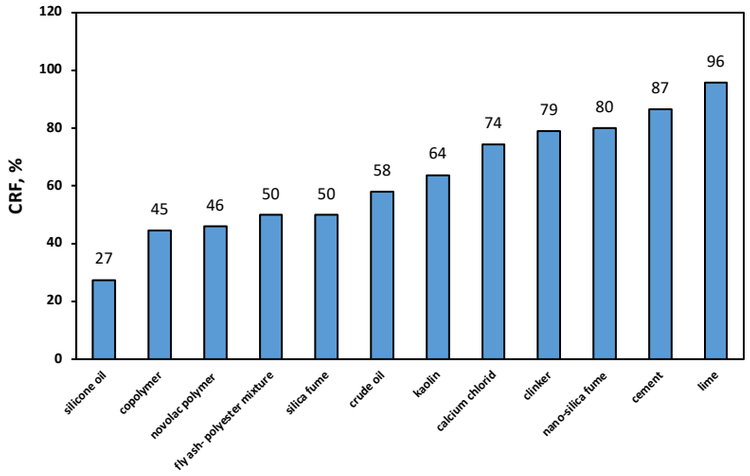


FIGURE 10. Variation of CRF with different chemical additives added to gypseous soils

Although all the additives reduced the collapsibility of gypseous soils, their efficiency as stabilizers depends on the type of additive used and this, in turn, depends on the type of reaction between these additives and gypseous soil. The positive effect of adding up to 3% polymer additives (novolac polymer and co-polymer) has been attributed to their ability to increase the bonding between soil particles and, as a result, reduce the collapsibility (Mohammed et al. 2019). While the effect of oily composition additives, like crude oil and silicone oil, is represented by their water-proofing ability. These additives coat the soil particles, limiting gypsum dissolving (due to water soaking) while also controlling skeleton breakdown, and the collapsibility is reduced as a result of these processes (Harris et al. 2005; Aziz & Ma 2011). Nano additives, such as nano-silica fume, on the other hand, have a large surface area that makes them excellent in controlling collapsibility. These additives regulate the dissolution of gypseous soils by adhering to them and by preventing moisture from reaching soil particles by surrounding them (Al-Obaidi et al. 2020; Al-Murshedi et al. 2020).

The addition of kaoline as an additive can delay the dissolution of gypsum in soils. This material coats the particles and fills the pores between them, delaying gypsum decomposition and reducing the soil's collapsibility. According to literature, 6% of kaoline is enough to produce the mentioned effects (Al-Neami 2000). While the pozzolanic reaction of traditional additives (e.g. lime) has its efficiency as a successful gypseous soils stabilizer. The treating of gypseous soils with 5% lime has been found highly effective in reducing the collapsibility to a minimum value at which the treated soils are considered as non-problematic (with respect to collapsibility) (Al-Janabi 1997).

Treating the gypseous soils with a stabilizer from the group of salts additives can decrease their collapse potential. For example, the addition of 2.5% of calcium chloride to gypseous soil reduces its collapsibility due to increasing the concentration of cations like calcium (Ca^{++}) in the soil, thus, the solubility of gypsum decreases. Also, the dissolution of calcium chloride in water reduces the ability of water to dissolve the gypsum, in other words, decreases the solubility of the gypsum. In general, it can be said that stabilizers which contain calcium cations can mitigate the collapsibility of gypseous soils (Al-Busoda 1999; Al-Taie et al. 2019).

The effect of different stabilizers on the shear strength of gypseous soils has been included in the present review. The stabilizers reviewed here are crude oil, cutback asphalt, nano-silica fume, and silica fume (Al-Abdullah et al. 2000; Karim et al. 2013; Kadhim 2014; Shaker 2017; Al-Adhamii et al. 2020; Al-Murshedi et al. 2020; Al-Obaidi et al. 2020). Some of these additives cause a decrease in shear strength parameters, while other additives lead to an increase in the values of these parameters. According to previous studies, the cohesion of gypseous soil treated with 9% of crude oil has been considerably increased (3 folds), while the value of friction angle is reduced to about one-third. The viscosity of the crude oil is the main factor in this behavior, where the crude oil works as a connector to the particles of soil, and as a result, increases the cohesion of the soil. While the reduction in internal friction is due to the formation of a membrane (of the crude oil) coating the soil particles which reduces the friction between the particles of the gypseous soil (Al-Adhamii et al. 2020).

The shear strength parameters of the gypseous soils are affected by nanomaterial stabilizers. Due to the cementation action, the apparent cohesion of the soil increases when nano-silica fume is used as an additive. In turn, the internal friction slightly increases with the presence of nano-silica fume, however, both strength parameters are positively affected by curing time (Albusoda & Khdeir 2018; Al-Murshedi et al. 2020). Also, the cutback asphalt has been used to improve the strength of gypseous soils (Kadhim 2014; Shaker 2017). There is a contradiction between the findings of various studies on the use of cutback asphalt as a stabilizer for gypseous soil. Some studies indicated that the use of specific percentages of cutback asphalt (ranged from 2% to 6%) helps to improve the strength of the soil by increasing its bearing ratio (Kadhim 2014). On the contrary, other studies indicated that adding 3% to 15% of cutback asphalt reduces the bearing capacity of gypseous soil due to reducing the values of its shear strength parameters (Shaker 2017).

CONCLUSION

This review paper considered the properties of gypsum, gypsum effect on soil properties, the main geotechnical properties of gypseous soils, and different important additives and methods used in gypseous soils problems mitigation. The review shows that depending on the type and amount of impurities, gypsum takes on different shapes and physical appearances (colors and shades). It has a low density (approximately 2.3) and hardness. Due to its changing chemical structure, gypsum is an unpredictable material. It is the most common source of sulphate in soils, and it has a significant impact on their geotechnical properties. The specific gravity of gypsum-rich soils is lower. The specific gravity of gypseous soils is influenced by soil gradation and type, gypsum and organic matter content, and the presence of other salts besides gypsum. The amount of gypsum in gypseous soil determines its compaction properties. These properties are greatly influenced by soils containing more than 15% gypsum. As a low-density substance, gypsum is used as a filler in the soil matrix and as a cementing additive. The compaction characteristics of gypsum are also affected by its grain size. On the other hand, depending on its content, gypsum acts either as a stabilizer or destabilizer agent to the shear strength of soils. If the content of gypsum in soils is lower than (10% - 20%), it acts as a stabilizer, for further content, gypsum has a reverse effect on the shear strength of gypseous soils. Finally, because of its widespread distribution in various areas, a variety of techniques for stabilizing gypseous soils have been developed. Mechanical procedures (e.g., compaction, replacement, reinforcement, etc.) and chemical treatment are examples of these techniques. Chemical additives (conventional additives, salt additives, industrial and household wastes, nanomaterials) are more effective than other techniques. However, there are several limitations to using calcium-containing chemical additions in the stability of clay gypseous soil. Such additives should be used with caution since they might have disastrous consequences. In fact, further investigation for such a topic is highly recommended for future work.

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DECLARATION OF COMPETING INTEREST

None

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