Research Article

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Mitigation of collapse characteristics of gypseous soils by activated carbon, sodium metasilicate, and cement dust: An experimental study

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Abstract: This study includes adding chemicals to gypseous soil to improve its collapse characteristics. The collapse behavior of gypseous soil brought from the north of Iraq (Salah El-Deen governorate) with a gypsum content of 59% was investigated using five types of additions (cement dust, powder sodium meta-silicate, powder activated carbon, sodium silicate solution, and granular activated carbon). The soil was mixed by weight with cement dust (10, 20, and 30%), powder sodium meta-silicate (6%), powder activated carbon (10%), sodium silicate solution (3, 6, and 9%), and granular activated carbon (5, 10, and 15%). The collapse potential is reduced by 86, 71, 43, 37, and 35% when 30% cement dust, 6% powder sodium meta-silicate, 10% powder activated carbon, 6% sodium silicate solution, and 10% granular activated carbon are used, respectively.

Keywords: gypseous soil, collapse potential, active carbon, metasilicate, cement dust

1 Introduction

Gypseous soils are found in many different parts of Iraq, accounting for more than 20% of the country's total area [1]. In aired and semiarid locations, gypseous soil is one of the most important high salt soils. The failure problems of the gypseous soil occur due to the dissolution of gypsum and soil softening during leaching (if the flow of water is continuous) [2].

Gypseous soils (also known as gypsiferous soils) have a significant amount of gypsum hydrated calcium sulfate ($CaCO_4{\cdot}2H_2O$). "Any unsaturated soil that, when wetted with or without extra loads, suffers a radical rearrangement in particles as well as a huge change of volume" is how collapsible soils are characterized. Due to the dissolution and softening of gypseous soils, they lose their strength with a dramatic increase in compressibility when moist [3]. Gypseous soils are classified as very sensitive to environmental conditions. Most of the soils suffered from many geotechnical problems that were dependent on many factors like soil composition, type of soil, and mineralogy, and especially, the problems related to the mechanical and physical properties of soils [4]. Gypseous soil, like any other soil, deforms under loading. This deformation differs greatly between the dry state and the soaked state [5].

Because of the dissolution of gypsum, several projects on gypseous soils suffered cracks, tilting, collapse, and soil leaching. The two types of collapse are soaking and leaching. Soaking collapse occurs when dry or partially wet soil is soaked with water at high pressure and without a flow of water, whereas leaching collapse is caused by the flow of water through the soil under any given pressure. Water percolation, water table fluctuation (capillary action), and diffusion are all methods for removing soluble salts like gypsum from the soil section, and this process is called leaching [6]. The gypseous soil sample exhibits a significant amount of leaching strain and is larger than the initial settlement as well as has no definite endpoint upon gypsum dissolution continuation and leaching from the soil sample [7].

The objective of this study is to select the optimal material to mitigate the collapse potential of gypseous soils by using various chemical additives and find the best material to meet the study's objective.

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2 Identification of gypseous soils

According to the Alphen and Romero classification, more than 2% gypsum by weight is required in the soil to be gypseous soil [8]. Al-Barazanj classified gypseous soils into two categories: those containing more than 50% gypsum and those containing less than 50% gypsum. For more than 50% of gypsum contained in the soils, non-gypsiferous materials' textures have been used to explain words such as loamy gypsiferous materials [9]. For the soils that contain less than 50% gypsum, according to the percentage of gypsum, five subgroups are proposed, as shown in Table 1.

3 The problems with the gypseous soils

Many engineering challenges arise as a result of gypsum dissolution when soil is wetted with water. These issues cause the structures to crack, tilt, and eventually collapse [1].

Several failure cases had been taken place in Iraq in different structures as shown below:

- Tourist hotel in Samarra.
- Training center in Tikrit.
- Kerbala elevated water tank.
- Dujail communication center.
- Habbaniya tourist village.
- Baiji Refinery due to softening of the soils (shear strength characteristics).

The Iraqi largest dam lies in north-west of Iraq [3].

In some cases, replacing expansive soil at a shallow depth will solve the problem; in other cases, keeping a constant soil moisture content can help mitigate the damage caused by expansive soils [10,11].

Table 1: Classification of gypsiferous soils [9]

Gypsum content (%)	Classification
0.0–0.3	Non-gypsiferous
0.3–3.0	Very slightly gypsiferous
3.0–10	Slightly gypsiferous
10–25	Moderate gypsiferous
25–50	Highly gypsiferous

4 Previous research on the treatment of gypseous soils

Many investigators in Iraq have used a variety of approaches for research purposes in the last two decades. Various chemical and physical therapy approaches are used for conducting laboratory work to improve the behavior of gypseous soils by mixing them with other materials. Nanomaterials are considered one of the important modern methods used to improve the soil to reduce undesired properties [12]. Also, bacterial calcium carbonate precipitation has been used in improving gypseous soils [13]. Gypseous soils may be treated chemically using calcium chloride [14], cement, lime, and crude oil products, which are the most commonly recommended remedial materials, or physically by enhancing the gypseous soils' geotechnical properties to reduce the impacts of gypsum dissolution [15–17], as shown in Table 2.

5 Experimental work

5.1 Materials

5.1.1 Soil

A disturbed natural gypseous soil sample, brought from the governorate of Salah El-Deen in the north of Iraq, located by the red point in Figure 1, with gypsum content of 58.9% from a depth of 1.0 m, was used in this investigation. The samples were collected, air-dried, pulverized, and well mixed before being prepared in double nylon bags. A laboratory testing program was then performed to determine the soil's physical, mechanical, and chemical characteristics; the results are presented in Table 3.

5.1.2 Improvement materials

There are five types of additive materials: cement dust (10, 20, and 30%), powder sodium meta-silicate (6%), powder active carbon (10%), sodium silicate solution (3, 6, and 9%) and granular activated carbon (5, 10, and 15%).

5.2 Soil–chemical mixing

The amounts of materials that are used to produce mixtures of various combinations based on the percentage by

Table 2: Previous studies on treatment methods for improving gypseous soils

Authors	Types of gypsiferous soils	Method of treatment	Expected improvement
Albusoda and Khdeir [12]	Poorly graded sandy gypseous soil	Mixing gypseous soil with nano-silica fume and nano-fly ash	The collapsibility lowers dramatically to over 83% at the optimum percent of fly ash and nanomaterial (2% fly ash) and (4% silica fume), indicating an improvement in collapse potential as a treatment material
Salman *et al.* [13]	Sandy gypseous soils	The use of the bacterial calcium carbonate precipitation	The results showed a recognized reduction in collapse behavior
Al-Busoda [14]	Sandy gypseous soils	Treatment with dehydrate ($CaCl_2{\cdot}2H_2O$) calcium chloride	The result was significantly decreasing in the collapse potential when treated with 2.5% $CaCl_2{\cdot}2H_2O$ by weight as well as a decrease in the compressibility characteristics was noticed in unleached treated samples
Al-Gharbawi *et al.* [15]	SP, natural gypseous soil prepared at two relative densities 35 and 75%	Mixing natural gypseous soil with magnesium oxide and carbonated magnesium oxide	Applying 10% carbonated magnesium oxide for 3 h reduces the permeability coefficient by more than 100% for the samples of two relative densities and two testing techniques
Hayal *et al.* [16]	SP (poorly graded sandy gypseous soil)	Two types of nanomaterials were used in the lab tests (nano-silica and nano-clay) mixed with gypseous soils	The collapse potential (Cp) decreased by 91% when nano-silica was increased to 1%, also, adding nano-clay to the soil reduced the collapse potential (Cp) by 73.75%, making the soil non-problematic
Al-obaidi *et al.* [17]	Poorly graded sandy gypseous soil with no fines (SP)	Combining gypseous soil with silica fume and nano-silica fume	Nano-silica fume reduces the CP of gypseous soil and improves its behavior
Abid Awn *et al.* [18]	Elastic silts gypseous soil	Mixing gypseous soil with Portland cement	The results of the laboratory for gypsiferous soil models treated with cement and compaction, experiments on model samples indicate a large reduction in collapsibility. The treated model had a reduction in collapsibility of (95%) when 10% cement was added, and the soil density was increased
Abood [19]	The first type was clayey gypseous soil while the second type was sandy gypseous soil	Two main types of gypseous soils with varying gypsum concentrations with the sodium silicate solution	It was shown that the addition of sodium silicate improved the strength and reduced collapsibility of the gypseous soil
Al-Busoda and Al-Rubaye [20]	SP-SM	The model pile was constructed on gypseous soil with a 42% gypsum content	Model piles embedded in gypseous soil were subjected to compression axial model pile load testing before and after soil saturation at 7% initial degree of saturation. The results of the pile load tests found that Shen's method was shown to produce a nearly good result for all the model pile load testing. Because of the loss of gypsum cementing activity caused by wetting, a significant reduction in bearing capacity was seen when the model pile was loaded after it had been soaked for 24 h
AL-Busoda and Alahmar [21]	Poorly graded sand (SP)	Dry and soaked states' dynamic response by using foundation rest on collapsible soil	The amplitude of displacement in the dry condition is higher than in the soaked state, according to the results, in the soaked state, the resonance frequency is higher than in the dry state. Also, an increase in eccentric mass leads to an increase in

(*Continued*)

Table 2: *Continued*

Authors	Types of gypsiferous soils	Method of treatment	Expected improvement
			displacement amplitude for a given frequency. When eccentric mass is raised, an increase in resonant frequency can be observed
Al-Busoda and Hussein [22]	Poorly graded sand (SP)	Shallow footing bearing capacity of compacted dune sand over reinforced gypseous soil	The most efficient thickness for a dune sand layer with geotextile at the interface was determined to be almost equivalent to the foundation width at this depth, the collapse settlement reduction factor (csrf) increases to 7%. Furthermore, bearing capacity increases to (1.5–2.0) time under concentric loads and (2.5–3.0) time under eccentric loads

dry weight of the soil sample correspond to the convenient circumstances and increase the accuracy of test results. To obtain a uniform mixture, a desired amount of materials was thoroughly mixed with the soil sample. A preset amount of material was added to the soil and well mixed in the dry state until the mixture seemed uniform in texture and color, after which a required amount of distilled water (3% of the soil sample dry weight) was added and it was thoroughly remixed. Following the completion of the period, the experimental procedures were carried out by using an oedometer device (singe collapse test).

6 Results and discussion

6.1 Collapsible test results without adding materials

A typical reaction in which a seating stress of 25 kPa was used to create the initial condition. The samples were prepared at the field to a dry unit weight of 14.63 kN/m^3 by making a gentle tamping on the sample in a compaction mold. To get the collapse test specimen as standardized by ASTM D5333, the soil sample is loaded gradually from initial conditions until it reaches a vertical stress of 200 kPa in an oedometer device. The soil sample is then soaked in water for 24 h. Due to the soaking process, additional settlement is observed at 200 kPa stress levels. The test continues with more loading and unloading, as in a conventional consolidation. The soil sample's collapse potential (CP) is equal to 7.21, as shown in Figure 2, according to the results of the collapse test and according

Figure 1: An aerial photo illustrates the location of soil samples in Salah El-Deen governorate/Iraq.

Table 3: Results of laboratory testing on gypseous soil

Property	Results	Specifications
D 10	0.05	ASTM D422 and ASTM D2487
D 30	0.2	
D 60	0.5	
Coefficient of uniformity (Cu)	1.6	
Coefficient of curvature (Cc)	10	
Specific gravity (Gs)	2.34	
Relative density	0.53	ASTM D2049-6
Angle of internal friction ϕ	29.7	ASTM D3080
Maximum dry unit weight (γ_{dmax}) (g/cm^3)	1.31	ASTM D3080
minimum dry unit weight (γ_{dmin}) (g/cm^3)	1.11	ASTM D2049-69
Gypsum content (%)	59	Al-Mufty and Nashat [23]
Single collapse test, CP (%)	7.38	ASTM D5333

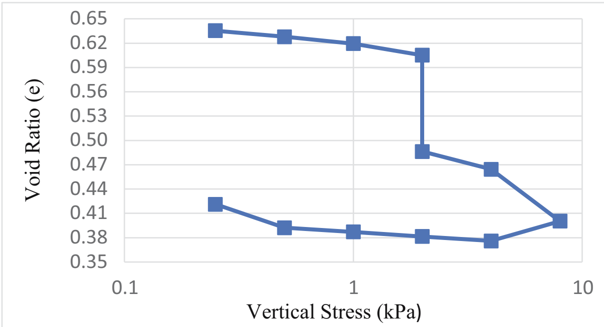

Figure 2: Single collapse test results on the natural soil.

to ASTM D5333, the soil is classified as moderately severe. A similar finding can be seen in [22].

6.2 Effect of adding materials

6.2.1 Granular activated carbon

Granular activated carbon (GAC) is a type of carbon with a bigger particle size than powdered activated charcoal and is often used to filter pollutants from water and air, among other things. Because of its low cost and excellent adsorption effect, it is used in various popular treatment sectors. GAC was added to the soil in percentages of 5, 10, and 15%, and the results indicate the enhancements shown in Figure 3. The results of the single collapse test on gypseous soil improved by adding 5% GAC show that collapse has been reduced to 5.55%, while the samples treated with 10% GAC show a decrease in the void ratio at a pressure of 200 kPa from 0.610 to 0.532, resulting in a reduction in the collapse potential to 4.7%. The void ratio changed from 0.596 to 0.516 when the soil samples were treated with 15% GAC, and the collapse potential was reduced to 4.9%. Because the physical mechanism of GAC, which has micropores, provides ideal circumstances for good adsorption, since adsorbing material can interact with several surfaces at the same time, GAC adsorbs some gypsum salt, lowering the collapse potential. However, adding GAC to a higher concentration than the optimum value induces particle agglomeration, which severely affects the gypseous soil's mechanical characteristics.

6.2.2 Powder activated carbon

Powder activated carbon (PAC) is a finer version of the GAC material GAC. PAC consists of crushed or powdered carbon particles, with 95–100% of them passing through a mesh filter. As specified in ASTM D5158-98, particles passing through an 80-mesh (0.177-mm) screen have excellent absorption, low attrition loss, and high density. Figure 4 illustrates the results of the single collapse test performed on gypsum soil samples treated with 10% powder activated carbon, in which the void ratio changed from 0.616 to 0.549 under compression at 200 kPa, lowering the collapse potential to 4.1%. The decreased collapse potential in treated samples could be explained by the tight binding in the binder. The decreased collapse potential in treated samples could be explained by the effect of the binder. Because the small particles bind the gypsum particles, they limit the influence of water and fill holes in the soil better than GAC, which has a greater particle size.

6.2.3 Sodium silicate solution

A mixture of silica (often quartz sand), caustic soda, and water can be treated with hot steam in a reactor to make a sodium silicate solution. The sodium silicate solution was applied to the soil at three different percentages: 3, 6, and 9%. Figure 5 shows the results of the single collapse test

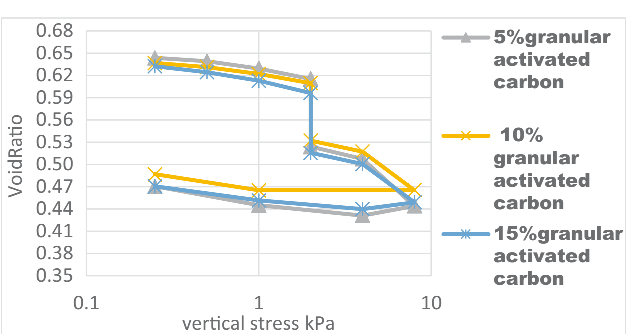

Figure 3: Collapse test results for soil treated with (5, 10, 15%) GAC.

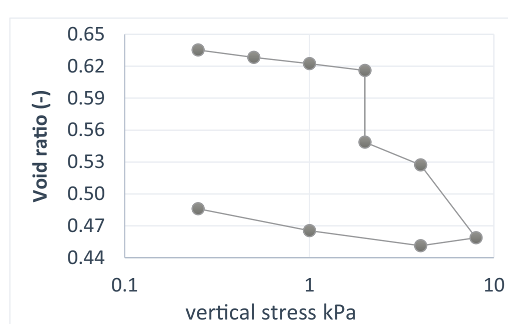

Figure 4: Collapse test results for soil treated with 10% powder activated carbon.

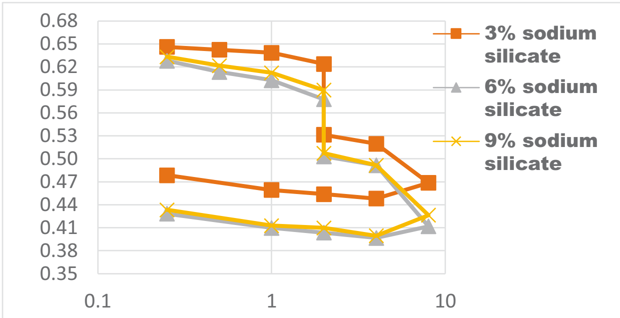

Figure 5: Collapse test results for soil treated with (3, 6, and 9%) Sodium silicate solution.

of gypseous soil treated with a 3% sodium silicate solution. It has been noticed that the collapse potential has decreased to 5.62% while it decreases to 4.53% when treated with a 6% sodium silicate solution. The results of a single collapse test on gypseous soil samples treated with a sodium silicate solution of 9% resulted in a collapse potential of (5%). In aqueous solutions, sodium silicate interacts with soluble calcium salts (like gypsum) to generate insoluble gelatinous calcium silicates. Because the hydrated calcium silicates act as cementing agents [24], the collapse potential is reduced. Similar results were found in [19].

6.2.4 Powder sodium metasilicate

Powder sodium metasilicate was added to the soil at a rate of 6%, and the following improvements were observed. When the soil is wet, the dissolution of gypsum in the soil causes bonds between grains to break down, resulting in the initial collapse of the metastable structure of the soil. Molecular forces between particles become weak as water saturation rises and their strength diminishes. So, the strongest force is used to cement the bridges Furthermore, the collapsibility of gypseous soil is governed by the inter- and intra-aggregate distortion and size. The cementing bonds between the particles were broken down after full inundation of collapsible soil. Improvements were noticed after 6% powder sodium metasilicate was added to the soil as shown in Figure 6. It is worth noting that the hazard of collapse has been reduced by 71% because the used material works as a cementing agent between soil particles, forming a different type of bond that resists the inundation of collapsible soil and reduces collapse.

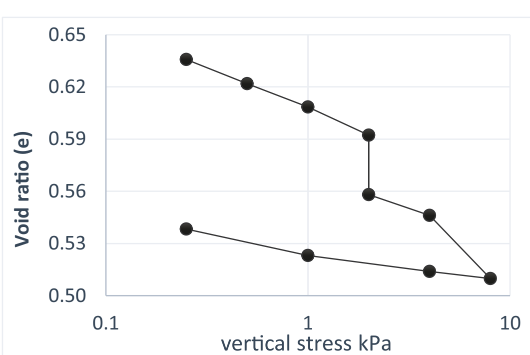

Figure 6: Collapse test results for soil treated with (6%) powder Sodium metasilicate.

6.2.5 Cement kiln dust

Cement kiln dust (CKD) is a waste by-product of the cement manufacturing. This substance is a health hazard, a storage issue, and a possible pollutant. Some of these issues could be solved by using such materials in civil engineering projects to enhance marginal materials. The CKD was added to the soil in percentages of 10, 20, and 30%. The result of the single collapse test using gypsum-saturated soil samples is shown in Figure 7. The risk of collapsing has been minimized to a minimum (80%). The results on gypsum soil samples treated with 20% cement dust reveal that reducing the collapse (83%) and applying 30% cement dust reduces the collapse by 86%. The void ratio decreased as a result of adding material to the soil specimens, reducing the risk of collapse. The collapse potential is minimized since the constituents of cement dust are virtually comparable to those of Portland cement, which worked as a coating and binding material that resists the water effect, which is consistent with Abid Awn's previous study on gypseous soil [18].

Figure 8 represents the percentage of improvement of CP of treated soil with different chemical additives and Table 4 summarizes the degree of collapse potential improvement.

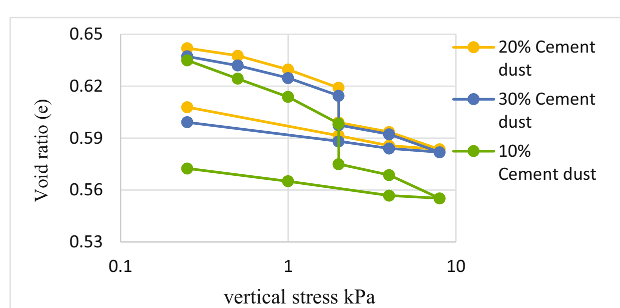

Figure 7: Collapse test results for soil treated with 10, 20, and 30% cement dust.

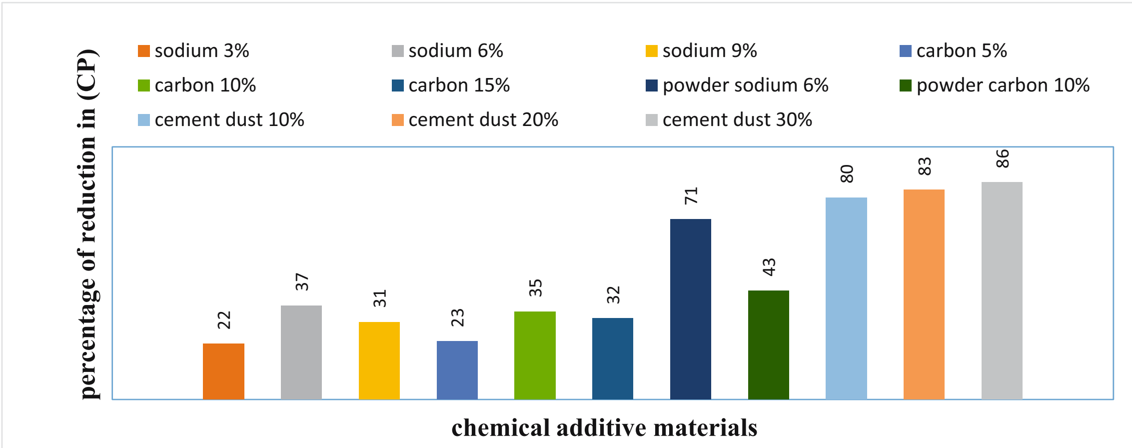

Figure 8: Percentage of improving the CP of treated soil with chemical additive materials.

Table 4: Degree of collapse potential improved

Soil	Percent	Collapse potential	Improve percent
Natural soil		7.21	–
Sodium silicate solution	3	5.62	22.05
	6	4.53	37.17
	9	5	30.65
Granular activated carbon	5	5.55	23.02
	10	4.7	34.81
	15	4.9	32.04
Powder sodium metasilicate	6	**2.07**	71.29
Powder activated carbon	10	4.1	43.13
Cement dust	10	**1.42**	80.31
	20	**1.22**	83.08
	30	**1.03**	85.71

Bold values indicate that the relevant additive reduced the collapse potential from Moderately severe to Slight.

7 Conclusions and summary

Many experiments on collapsible soil (gypseous soil) were carried out in this research by mixing it with various amounts of additional materials (cement dust, GAC, powder active carbon, sodium silicate solution, powder sodium metasilicate) that were mixed in various ways and percentages in this investigation as cement dust (10, 20, and 30%), GAC (5, 10, and 15%), powder activated carbon as (10%), sodium silicate solution (3, 6, and 9%) and powder sodium metasilicate (6%) to investigate the collapse potential (CP). The following conclusions are possible to write:

1. Cement dust: When 10% of cement dust was added to the soil sample, it resulted in a decrease in collapse potential (CP) of about (80%). Then when add 20% the collapse potential (CP) will decrease to (83%), and with the increase of additive to 30% will decrease the collapse to (86%). The optimal percentage to improve the soil with this material is 30%.
2. Granular activated carbon: When 10% of GAC was added to the soil sample, it resulted in a decrease in collapse potential (CP) of about (23%). Then, the collapse potential (CP) increased with an increase of additive. The optimal percentage to improve the soil with this material is 10%.
3. When adding a 6% sodium silicate solution to the soil, the collapse potential (CP) decreased. By using 6%, the percentage of the decrease in CP is about 37%; afterward, this percentage increases again; the sodium silicate solution additive effect will change the rate of collapse severity from moderately severe to moderatecase.
4. Increasing the powder activated carbon to 10% causes a reduction in the collapse potential (CP) by 43%, indicating that the additive changes the soil from a moderately severe case to a moderate case.
5. Increasing the amount of powder sodium metasilicate reduces the collapse potential (CP) by 71%, indicating that the additive changes the soil from a moderately severe to a slightly severe case.
6. The sodium silicate solution has water in about (63)% of the weight that may cause the dissolution of gypsum in gypseous soils and increase the collapse potential more than powder sodium metasilicate.

7. Powder activated carbon coats the gypsum particles and fill the void in the soil because the tiny particles are better than GAC, which has a large particle size.

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