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Using a Laboratory Model Test to Assess the Collapsibility of a Gypseous Soil Improved with Geogrid and Cement Kiln Dust

Kamil S. Kamil[a], Ahmed H. Abdulkareem[a], Nabeel S. Mahmood[b]

[a] *Department of Civil Engineering, University of Anbar, Ramadi, Iraq*

[b] *Department of Dams and Water Resources Engineering, University of Anbar, Anbar, Iraq*

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ABSTRACT

Collapse of gypseous soils may cause excessive settlement and serious damage to engineering structures. Various improvement approaches, such as mechanical techniques and chemical additions, have been used to reduce the collapsibility of these soils. The odometer test has traditionally been used to assess the collapsibility of the improved gypseous soils; however, because the small size of test specimens, this method may not adequately reflect field conditions. In this research, a laboratory model test of 600 x 600 x 600 mm with a model footing of 100 x 100 mm was developed to measure the collapse characteristics of a gypseous soil. The top layer underneath the footing was improved by compaction, cement kiln dust (CKD), geogrid, and a combination between CKD and geogrid. The top layer was improved at two values of thickness of 50 and 100 mm. The results obtained from this study indicate that the values collapsibility settlement reduction factor for compacted soil and the soil treated with CKD were 75 and 82%, 89% receptively. These values increased up to 95 % when a combination of CKD and geogrid was applied. As discussed herein, the aforementioned treatment methods can effectively be used to improve the collapsibility of gypseous soils.

1. Introduction

Gypsum content in soils may cause problems to foundations and geotechnical projects due to the high rate of desolation of gypsum that can lead to large deformations or massive collapse. Gypsum is frequently produced through the weathering of rocks that include various types of minerals. The highest solubility of gypsum is 2.6 g/l between 33 and 50 oC. Temperature and the presence of other salts in the soil have a direct impact on gypsum solubility (Al-Zabedy and Al-Kifae, 2020). Gypseous soils may be found all over the world, although they are most common in dry and semi-arid areas. Gypseous soils in Iraq covers 20–30% of Iraq's land. Therefore, some buildings in Iraq have developed various patterns of fractures and uneven deformations, mostly as a result of the exposure to water (Al-Saoudi et al., 2013).

* *Corresponding author.*E-mail address: kam21e1012@uoanbar.edu.iq

Collapsible soils are considered to pose significant geotechnical and structural engineering challenges all over the world. They need an open metastable structure or open porous fabric to be developed using various bonding procedures. (Al-Mukhtar and Al-Obaidi, 2022) and (Fattah et al., 2015) and reported that when soils are initially dry, volume changes that lead to collapse frequently happen in non-plastic or extremely low plasticity soils and are quicker than those seen during consolidation processes. Furthermore, inadequate compaction techniques, low moisture levels, and waste items can also cause soil to artificially collapse. Considering the above-mentioned bonding agents, one can utilize chemical cementing, simple capillary suctions, or clay buttresses to introduce and build bonds between the solid grains in the metastable open fabrics of collapsible soils. Many attempts have been made to improve the properties of gypseous soils using physical or chemical methods. Therefore, it becomes more advantageous to employ natural resources and residual industrial materials to improve the characteristics of gypseous soil (Al-Obaydi, 2003) (Fattah et al., 2013). There have been various studies and trials to determine the best treatment for such soils. Some of them involved physical treatments like earth reinforcement, stone piles, compaction etc, while others involved chemical treatments like lime, cement kiln dust, kerosene, emulsified asphalt, or sodium silicate. All of these treatments are thought to be effective treatments for collapsible soil issues, as well as ways to reduce the volume changes of these this soil upon wetting (Kudadad, 2018) and (Al-Gharbawi et al., 2022).

Soil compaction is the process of reducing air voids between soil particles. Typically, this is achieved mechanically (Jawad and Jabbar, 2014). Different volumes of water are applied by (Jawad and Jabbar, 2014) to soil samples compacted at optimum moisture content (OMC) during 24 hours. After that, oedometer tests were conducted on the samples. It was observed that as the initial water content used to wet the soil increased, the collapse potential decreased. Therefore, the least expensive method of site soil improvement is often the mechanical method (compaction). It considered as a method to increase stability by enhancing soil cohesion and internal friction. Compaction also contributes to increase soil density and decrease soil permeability.

Earth reinforcement technique is one of the least expensive and most widely used method for enhancing soil when compared to other techniques. One of the materials used in reinforcement is geogrids, which has the advantages of high tensile modulus, extended service life, lightweight nature, and open structure (Kudadad, 2018). In general, compacted soils often have significant compression but low tension. In order to produce a soil mass with high compressive and tensile strengths, layers of compacted soil and geogrid are frequently combined. Since the geogrid has an open structure, compacted earth may bond in such regions.

Chemicals like curing agents (binders) are mechanically added or removed from soil mixtures to treat various soil types. The chemical stabilization is the change in physical and chemical properties of soil. Researchers have examined the effectiveness and suitability of employing alternative recycled materials and industrial byproducts to enhance different types of soil. The use of CKD compounds may be an alternative to lime since the stability of soil depends mostly on calcium in the form of lime. According to (Rahman et al., 2011), using CKD may result in cementing qualities that are comparable to Portland cement, which has a major impact on soil stability. The strength of bearing foundations is increased as a result of CKD enhancement of shear strength, reduction of soil shrinkage and swelling, and reduction of soil plasticity (Elbaz et al., 2019). According to (Rimal et al., 2019), soil stabilization is accomplished using cement or chemical additives, which can be either basic materials such as cement or waste products such as CKD. The author used CKD at 2.5, 5, 7.5, and 10% by weight of soil to stabilize the unconfined compressive strength of the soil.

The odometer test has been utilized to evaluate the collapse potential in the majority of previous research. The small dimensions of the test specimen used for odometer test may result in less accurate results of collapse values when utilizing various improvement techniques. Therefore, this study utilized a large laboratory model to measure the improvement in the collapse potential of a compacted gypseous soil after adding CKD and geogrid.

2. Materials and Methods

2.1. Soil

The soil utilized in this study obtained from a site in Al-Ramadi. The soil sample was taken at a depth of one to five meters. Mechanical pulverization was performed on it before being utilized in the laboratory. As can be seen from Fig. 1, the sample is a light brown fine to medium sand with some fine gravel and a significant quantity of gypsum in the form of crystal particles and white spots. The soil is classified as poorly graded sand (SP) by the Unified Soil Classification System (USCS). The physical and chemical properties of the soil are listed in Table 1.

(a) (b) (c)

Fig. 1 (a) Gypseous soil, (b) CKD material, (c) Geogrid reinforcement.

Table 1- Physical and chemical properties of the gypseous soil.

Test	Value	Standard
Water content%	6.6	(ASTM, D2216-98)
Specific Gravity, Gs (by Kerosene)	2.45	(ASTM, D854-10)
Maximum Dry Density (MDD) (g/cm^3)	1.625	(ASTM, D1557-09)
Minimum Dry Density (g/cm^3)	0.943	(ASTM, D4254-00)
Average Dry Density (g/cm^3)	1.28	
In Field Density (g/cm^3)	1.25	(ASTM, D1556-82)
Optimum Moisture Content (OMC) %	15	(ASTM, D1557-09)
Degree of saturation in field (%)	17.02	
Maximum void ratio, e_{max}	1.62	
Minimum void ratio, e_{min}	0.51	
Passing sieve (0.075mm) %	3.58	(ASTM, D422-07)
TSS (Total soluble solids) %	20	(BS, 1990)
O.M (Organic Matter) %	3.78	(ASTM, D2974–07)
SO_3 acid (Sulfuric Acid) %	17.2	(BS, 1990)
Gypsum Content %	37 % Highly gypsiferous	(Al-Mufty and Nashat, 2000)
pH	7.7	(ASTM, D6276-99)

2.2. Cement Kiln Dust (CKD)

The CKD is a by-product of cement industry that was obtained from Kubaisa Cement Factory in the Al-Anbar Governorate of Iraq. The material is generally grayish in color and according to the (ASTM, D422-07), 86.5% of CKD particles passed sieve No. 200 (0.075 mm). The specific gravity (Gs) of CKD was 2.12 and the CKD showed non-plastic characteristics. The results of chemical testing using X-ray fluorescence XRF are as listed in Table (2). The primary component of CKD and the basic element thought is responsible for the pozzolanic reactions of the CKD is calcium oxide.

Table 2-Chemical composition of the CKD

CKD	CaO	$Al2O_3$	SiO_2	Fe_2O_3	Na_2O	K_2O	MgO	MnO	SO_3
Percentage %	51.58	0.067	1.885	2.245	0.521	1.023	0.065	0.072	1.681

2.3. Geogrid

The geogrid material is produced by the Al-Latifia Factory for Plastic Mesh Geogrids which is triaxially supports soils. To ensure that the subsequent ribs have a strong subatomic direction that passes through the area of the significant indications, they are positioned in three different ways. According to the manufacturer, Table (3) shows the properties of the geogrid. The reinforcing of the geogrid is shown in Fig. 1-c.

Table 3- The properties of the geogrid

Property	Value
Roll Dimensions (m)	30x1
Grid Dimensions Aperture (mm)	8x6
Grid Weight (Kg/m2)	0.72
Thickness (mm)	3.3
Polymer	$HDPE_2$
Tensile Strength (kN/m)	7.65
Extension at load 10 %	3.2
Extension at 50 % from maximum load (kN/m)	6.8
Extension at maximum load (%)	20.2
Modules from Stress-Strain (kN/m2)	38251

2.4. Test Methods

2.4.1 Compaction Test

The stabilized soil was subjected to standard Proctor compaction testing which was conducted in accordance with (ASTM, D1557-09). In order to assess the engineering characteristics of gypseous soil beneath buildings, the CKD was added at 4%, 8%, and 12% by the weight of the soil. Fig. 2 shows the curves obtained from the compaction tests of the untreated soil and the soil-CKD combinations.

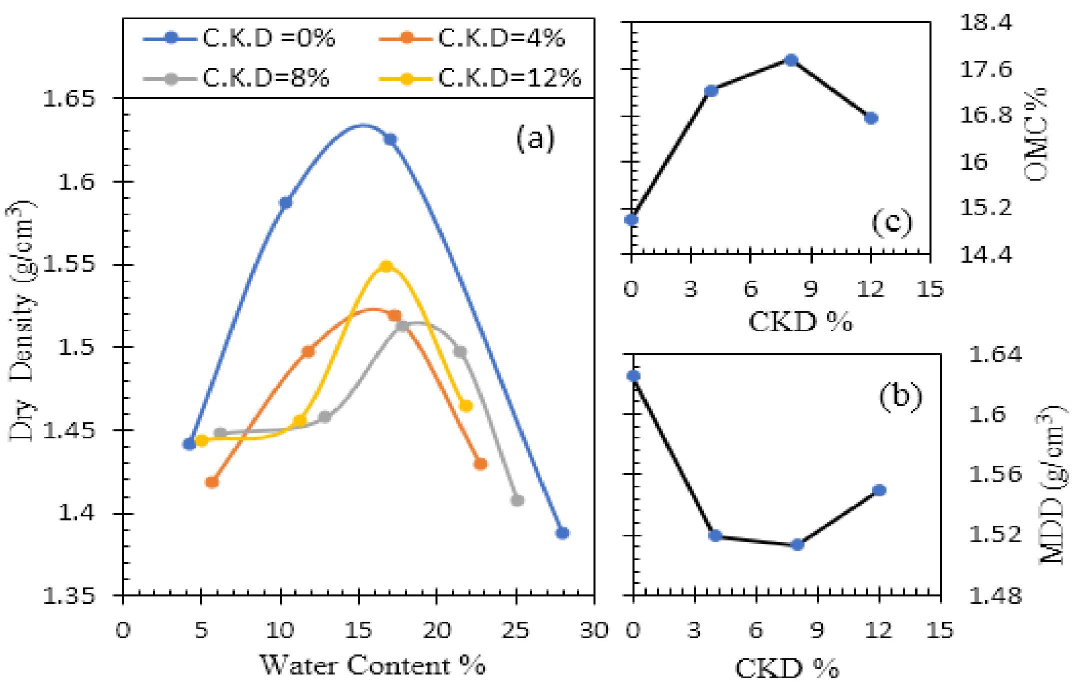

Fig. 2 (a) The compaction curves for stabilized soil at various levels of CKD, (b) Variation of optimum water content with CKD content and (c) Variation of maximum dry density with CKD content.

As the CKD content reached 12%, the maximum dry density (MDD) value was 4.68% less, and the OMC value was 11.8% higher than those for the samples with 0% CKD. Many earlier studies, like those by (Albusoda et al., 2012), have showed that when the CKD content increased, the MDD decreased and the optimum moisture content (OMC) increased. Due to their strong capacity to absorb more water required for hydration, CKD may be the cause of the increase in OMC that occurs when CKD content increased. The cationic reactions of CKD particles in the soil, which demand more water, may be the cause of the rise in the OMC. Therefore, the soil needs additional water to reach the optimum water content.

2.4.2 Collapse Test using Oedometer Apparatus

A single oedometer test was conducted to determine the effect of CKD on enhancing collapsible gypseous soils. The optimum percentage of CKD necessary to be used in the laboratory model test is determined from this test, according to a method similar to (Sakr et al., 2020). A number of collapse tests were performed on soil stabilized with different percentages of CKD (4%, 8%, and 12%) at seven days of curing, using maximum dry density and optimum moisture content for each percentage. The (ASTM, D5333-3) method was followed for conducting the test. The soil sample in this test was gradually loaded in a natural environment until it reached a vertical stress of 200 kPa. The soil sample was saturated in water for 24 hours, after which additional leveling was recorded at 200 kPa pressure levels as a result of the soaking procedure.

2.5. Laboratory Model Test

A laboratory model was used to analyze the behavior of gypseous soils before and after the application of the CKD and geogrid in order to understand their behavior before and after stabilization. Calculations were made to determine the collapse potential of the soil layers below the model footing level in three dimension's that were given different values for thickness, relative density, geogrid, and CKD content.

2.5.1 Model Description

The authors and production team created the loading mechanism, as shown in Fig. 3.

Fig. 3 The details of the laboratory model.

The model consists of three main parts: the box, the footing model, and the loading frame. The box of the model was 600 x 600 x 600 mm and was manufactured from 5 mm thick steel plates to provide more rigidity and resist the horizontal displacement of the soil. The box is positioned on a concrete block that should be kept balanced to prevent any system inclination and is placed on a four-tiered structure to facilitate the model movement. The footing is composed of strong steel squares of 100 x 100 x 6 mm. The footing model is positioned in the center of the box. The upper face of the footing is covered with thin steel plates. The upper plates have a suitable hole at the center of the footing used to convert the load to the footing. Loads are converted to the footing by a loading ram with a diameter of 40 mm and a length of 300 mm. A constant head was used during the saturation phase through two connected pipes. Each tank was filled with water from the same source. Static loads are placed in the center of the steel bar. A two-dial gauge with 0.01 mm sensitivity installed on the footing and secured to the horizontal steel rod by a magnetic holder that measure the soil settlement below the footing.

2.5.2 Laboratory Model Test Method

Seven layers of 50 mm thickness of dry soil were placed and compacted in the box by using a steel tamper (5.8 kg). The placement of the soil layers was achieved in the following ways:

- The soil layer right below the footing level (top layer) was improved either by compaction to the MDD and OMC without CKD or by compaction with CKD treatment. The thickness of this compacted layer was 0, 50, and 100 mm, which represents 0, 0.5, and 1 time the width of the footing model (B).
- The soil below the improved soil layer was compacted at three different values of relative density of 51, 65, and 77% to represent the range of the field density.

The load is applied using a technique that starts with an initial weight of 50 kg, which is equivalent to a stress of 49.05 kPa, and then increased by another 50 kg until it reached 200 kg, which is equivalent to a stress of 196.2 kPa (about 200 kPa). Each load is kept in place until there was no more dial gauge reading variation. A stress level of 196.2 kPa was applied and sustained for 24 hours. After that, the soil was saturated for 24 hours by permitting water to rise from the bottom of the box using pipes that provide water with a constant head of water 95cm. Following the 24 hours, more load increments were added, and the collapse for gypseous soil may then be determined.

3. Results and Discussion

3.1. Collapse Test from Oedometer Apparatus

Following the addition of the CKD material, the results of a conventional compaction test showed that treated soil performed better than untreated soil at maximum dry density and water content. Fig 4 presents the collapse in each test result. The results show that the addition of CKD by 4, 8, and 12% decreased the collapse potential by 56, 81, and 69%, respectively. The collapse potential decreased with increasing CKD materials to 8% then increased. This behavior of the soil may be attributed to the fact that these materials covered the soil particles and increased the bonding action between the soil particles. On the other hand, after 8% CKD content, the CKD caused the soil particles to flocculate and slide that led to a drop-in soil cohesion.

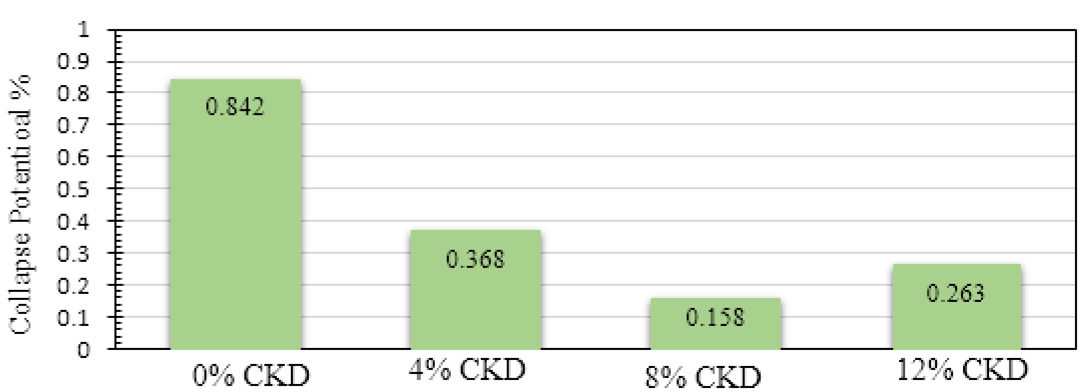

Fig. 4 The collapse potential variation with the percentage of CKD.

3.2. Collapse Test from the Laboratory Model Apparatus

3.2.1 The effect of relative density on the collapse

The collapse values (ΔS) represent the change in the magnitude of settlement (ΔS), at the same stress level, between the wet and dry states. The results of the tests conducted at three values of relative densities showed that as the relative density increased, the ΔS values decreased. For the relative densities of 51, 65, and 77%, the ΔS values were 45.65, 39.59, and 14.68 mm, respectively, as shown in Fig 5. This may be caused by an increase in soil stiffness and frictional forces.

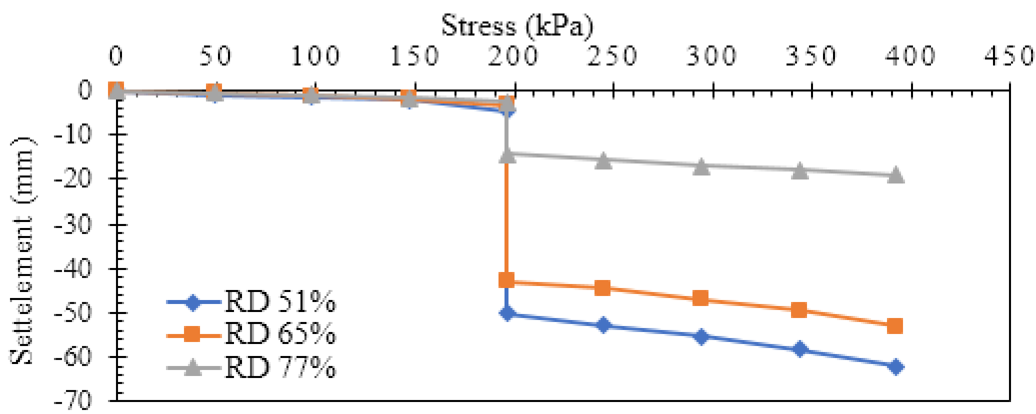

Fig. 5 The collapse results at different relative density.

3.2.2 The effect of the top layer compaction on the collapse

To evaluate the effect of compaction on collapsibility, the model test was conducted at the same relative densities of 51, 65, and 77%, but with replacing the top layer with soil that was compacted to the MDD and OMC. The thickness of the compacted soil was 0B, 0.5B, and 1B, as shown in Fig. 6 to 8. As the thickness increased from 0B to 1B, the ΔS values decreased by 80%, 87%, and 60% for the RD values of 51, 65, and 77%, respectively.

It can be seen that all the cases of using compacted soil below the footing resulted in a decrease in the collapse values. The collapse decreased as the thickness of the compaction increased. The soil compaction led to an increase in soil strength and frictional forces. However, punching failure occurred when compaction treatment was used only at 51% RD and 0.5B because of the placement of a strong layer above a weak layer. The values of collapse from relative density (65%) best represent the field density. The compaction thickness of 0.5 B is the most cost-effective thickness of the layer.

According to (Ibrahim et al., 2016) a collapsibility settlement reduction factor (CSRF) is used in the following formula to compare the results of the collapse test before and after employing various ways of treatment. The value of CSRF at a relative density of 77% was less than a relative density of 65% because of the small initial value of settlement at a high value of relative density, as shown in Fig. 9.

$$\boldsymbol{CSRF} = \left(\mathbf{1} - \frac{\boldsymbol{\Delta St}}{\boldsymbol{\Delta Su}}\right) \times \mathbf{100} \quad (1)$$

ΔSt = treated soil settlement change.
ΔSu = untreated soil settlement change.

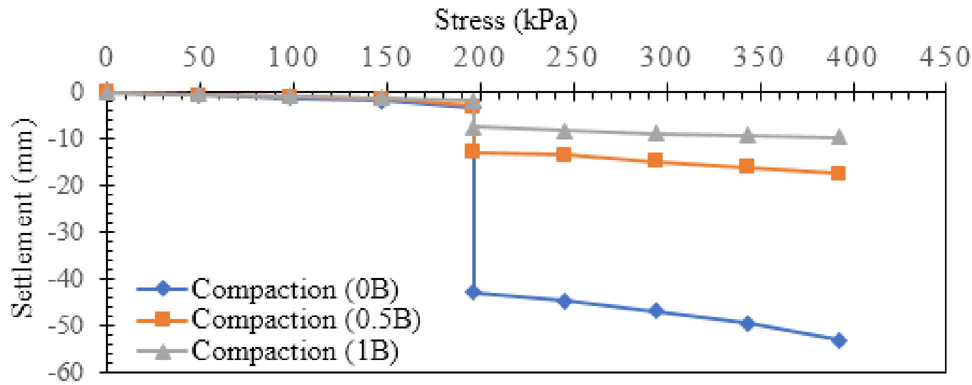

Fig. 6 The collapse results for the soil with RD=51%

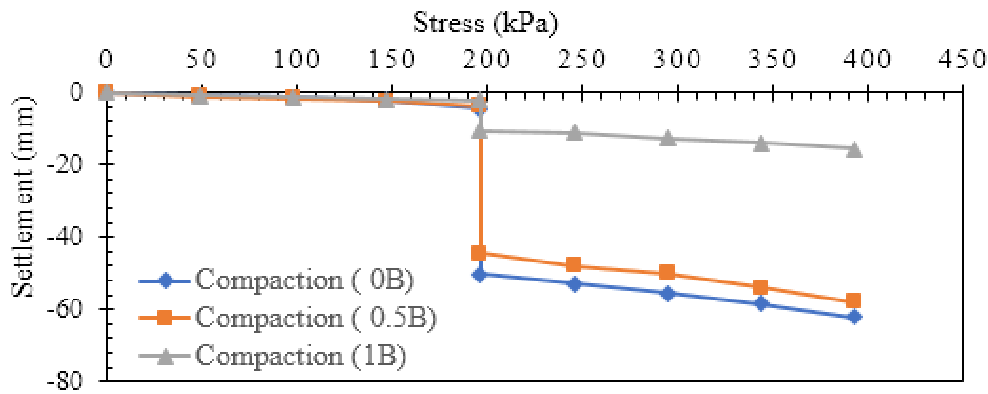

Fig. 7 The collapse results for the soil with RD=65%.

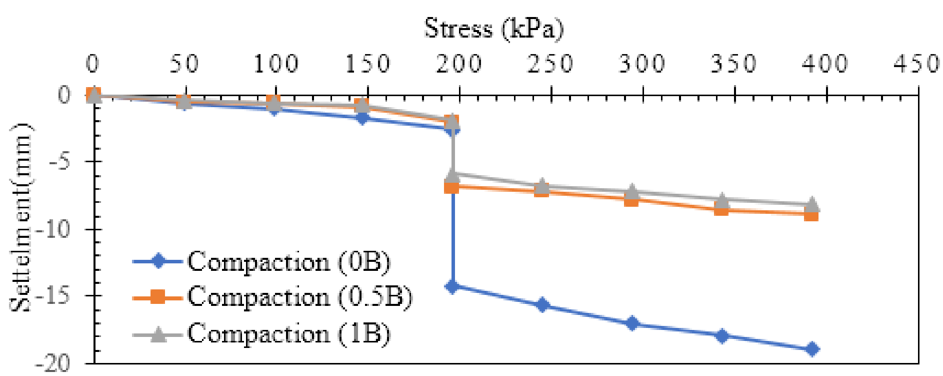

Fig. 8 The collapse results for the soil with RD=77%.

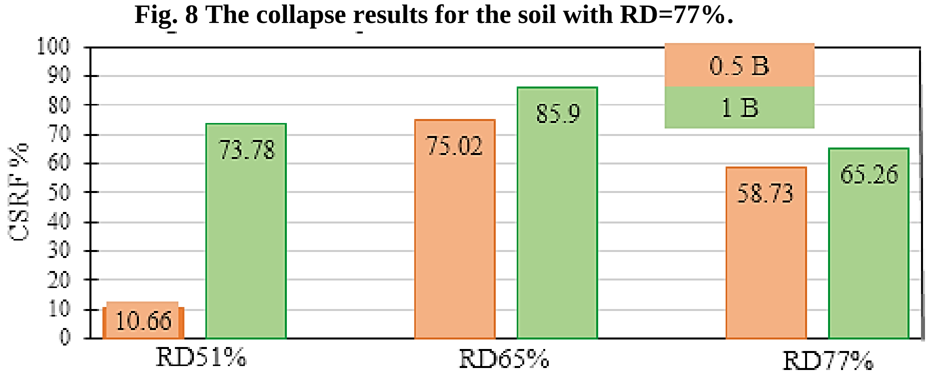

Fig. 9 The CSRF-RD

3.2.3 The effect of using CKD and Geogrid

The CKD amount that best represents the results of the odometer collapse test should be utilized in conjunction with a top layer compaction of 0.5 B of 65% RD, according to the previous section (3.1). The aforementioned combination is more accurate because it avoids punching failure, close to the field density, and economically accepted. The soil was further improved by using geogrid reinforcement. The soil was compacted at dry unit weight and a layer of stabilized soil with a 8% CKD was placed and cured for seven days at room temperature. The geogrid reinforcement was placed at depth of 0.5B. The outcome of the experimental work model with compaction treatment with geogrid at a relative density of 65% is shown in Fig10.

The observed relationships between stress and settlement showed a significant decrease in the soil collapsed, illustrating the strength increase from cementation. Moreover, from these data, it can be seen that the collapse value (ΔS) decreased from (9.89) mm without treatment to (7.14) mm with CKD, then decreased to (4.52) mm with geogrid, and finally decreased to (2.13) mm when compaction, CKD, and geogrid were used. In Figure (11), the collapsibility settlement reduction factor (CSRF) was used to compare the results of the collapse test before and after employing various techniques of treatment. According to these results, the maximum value of the CSRF reached 95% when using the three-treatment methods combination (compaction, CKD, and geogrid reinforcement) at 65% RD.

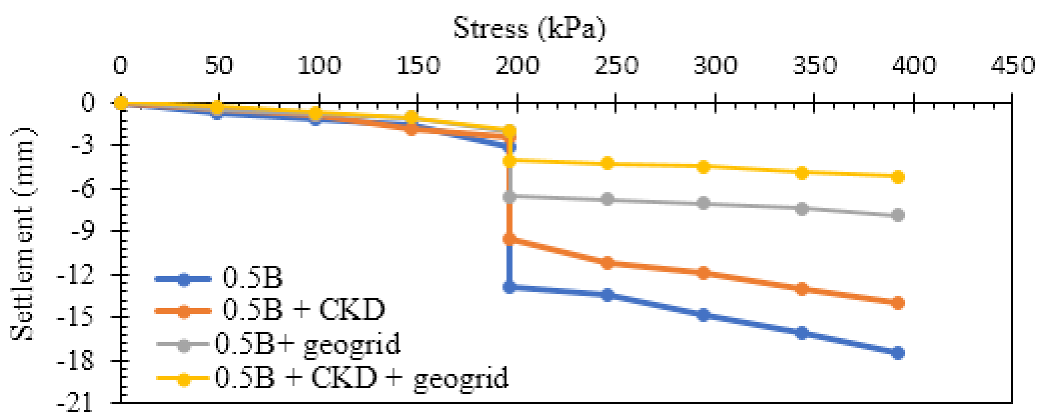

Fig. 10 The collapse values, as obtained from various treatment methods.

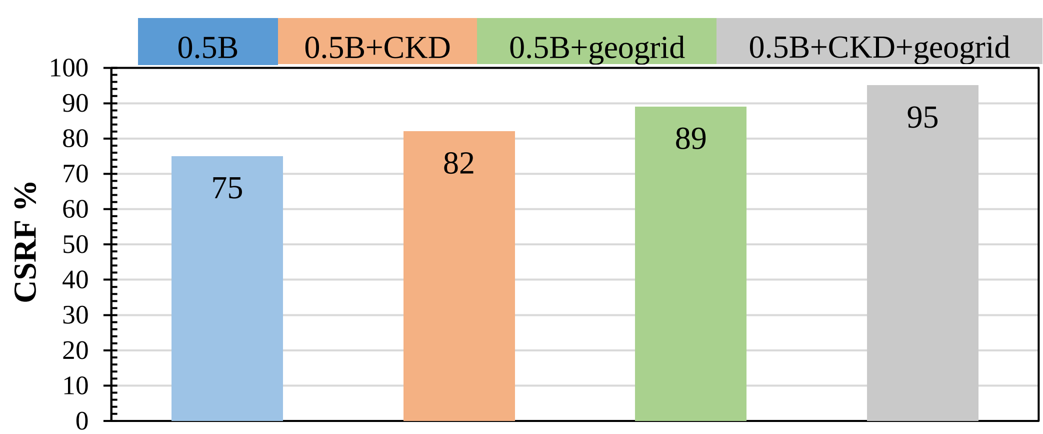

Fig. 11 CSRF – Variation Treatment.

4. Conclusions

This study investigated the effects of compaction, geogrid, and CKD on the collapse characteristics of a gypseous soil at static loading. Based on the test results, the following conclusions were reached:

- For all RD values, the collapse risk decreased as the top layer thickness, compacted to the MDD, increased.
- The improvement at RD of 65% and compaction thickness of 0.5B is suggested for the investigated gypseous.
- The collapsibility settlement reduction factor was 75 % at the top compacted layer (50 mm thickness).
- The collapsibility settlement reduction factor was 82% when the CKD was used in the top layer of 0.5B.
- The collapsibility settlement reduction factor was 89% when the geogrid was used in the top layer of 0.5B.
- The collapsibility settlement reduction factor was as high as 95% when the CKD was used in the top layer of 0.5B with the geogrid reinforcement which indicates that this combination is the most effective method to improve the gypseous soil.

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