Using a Laboratory Model Test to Evaluate Collapsibility of Gypseous Soils Improved by Sludge

Kamil S. Kamil[1, a*], Ahmed H. Abdulkareem[1, b] and Nabeel S. Mahmood[2, c]

[1]Department of Civil Engineering, University of Anbar, Ramadi, Iraq

[2]Department of Dams and Water Resources Engineering, University of Anbar, Ramadi, Iraq

[a]kam21e1012@uoanbar.edu.iq, [b]ahm1973ed@uoanbar.edu.iq and [c]nabeelshm@uoanbar.edu.iq

*Corresponding author

Abstract. Collapsibility of gypseous soils may cause excessive settlement and severe damage to engineering structures. Many improvement methods have been employed to reduce the collapsibility of these soils, such as by using physical methods or chemical additives. The collapsibility of the improved gypseous soils has conventionally been evaluated by using the odometer test, which may not accurately replicate the field conditions because of the small size of the test specimens. In this research, a laboratory model test of 600x600x600 mm with a model footing of 100x100mm was developed to measure the collapse characteristics of sandy soil with a gypsum content of 37%. The test was first conducted on specimens in the model at three different relative densities. The test was then performed after compacting the top layer of the test specimens [thickness from 50 to 100 mm] to the maximum dry density, as obtained from the Standard Compaction Test. Water treatment sludge was also used to further improve the top compacted layer. The results indicated that the collapsibility settlement reduction factor was 75% when the top layer of 50 mm thickness was compacted to the maximum dry density. Additionally, when the sludge was used with the top layer, the collapsibility settlement reduction factor was 86%.

Keywords: Gypseous Soil; Collapsibility; Improvement; Laboratory Model; Sludge.

1. INTRODUCTION

Gypseous soils may cause many problems for geotechnical projects as these soils can lead to large deformations in buildings or dams, which might finally result in a massive collapse [1]. Gypsum is frequently produced through rock weathering that includes various types of minerals. The chemical formula $CaSO4.2H2O$ describes the gypsum composition. Temperature and the presence of other salts in the soil directly affect the gypsum solubility, which can be as high as 2.6 g/l between 33 to 50 C° [2]. Gypseous soils are most common in dry and semi-arid areas and spread in many regions worldwide, including North West Asia, East Europe, and North America. Several studies have shown that approximately 20 to 30 percent of Iraq is covered with gypseous soil [3]. According to [4] [5], some buildings in Iraq have exhibited various patterns of cracks and nonuniform deformations as a result of the solution, followed by the collapse of the underlying gypseous soils. As reported by [6], when soils are initially dry, volume changes that lead to collapse frequently happen in nonplastic or extremely low plasticity soils and are quicker than during consolidation processes. Furthermore, adequate compaction techniques, low moisture levels, and waste material can prevent soil from collapsing artificially.

Preventing or reducing the collapsibility of gypseous soils has been an essential procedure when dealing with these problematic soils. There has been a need to produce a more stable structure or open porous fabric by using various bonding products. Gypseous soils have been the subject of several attempts to enhance their properties using physical or chemical techniques. According to [7, 8], specific materials such as clay or salts can cement soil particles together or produce capillary forces like suction. Furthermore, chemical cementing or clay buttresses can introduce and build bonds between the solid grains in the metastable open fabrics of collapsible soils [9]. It becomes more advantageous to employ natural resources and residual industrial materials to improve the characteristics of gypseous soils. Over the past three decades, various studies and trials have determined the best treatment for such soils. Some involved physical treatments like earth reinforcement, stone columns, and compaction, while others used chemical products such as lime, kerosene, bentonite, emulsified asphalt, or sodium silicate. All of these treatments were effective treatments for collapsible soil issues and ways to reduce volume changes.

Gypseous soils can be improved by reducing voids between the soil particles during soil compaction. Soil compaction is considered a cost-effective method for improvement as the stability of the soil is improved when cohesion and internal friction for this soil are improved. Furthermore, compaction also contributes to increasing the density and decreasing the permeability. Gypsum-compacted soils were investigated by [10]. Different volumes of water were applied to soil samples compacted at the optimum moisture content (OMC) for 24 hours, and oedometer tests were then conducted on the prepared specimens. The findings showed that as the initial water content of the mixture increased, the collapse potential decreased.

In soil improvement, chemical agents (binders) are added to treat different soil types [11]. Researchers have recently investigated the utilization of solid wastes, including sludge. Many previous studies have investigated the effectiveness and suitability of alternative recycled materials and industrial byproducts to enhance different soil types. In typical water treatment plants, the primary treatment processes that convert unfiltered water into filtered water include coagulation, flocculation, filtration, decantation, pH adjustment, fluoridation, and disinfection, which lead to the formation of sludge. Therefore, sludge is a byproduct of operations to treat drinking water. Using these materials to enhance soil is now possible because of the focus on sustainable systems and eco-friendly recycling. Sludge materials are widely utilized as filler materials in industries that depend on construction; thus, sludge analysis has been the subject of several experimental research [12]. The study of [13] utilized different percentages of sludge as soil stabilizers to increase the strength. This study used two amounts of compaction energy, 600 and 2,700 kN-m/m^3. The findings showed that even at a lower level of compaction energy (600 kN-m/m^3), adding the recommended amount of alum sludge (8%) greatly increased the strength of the soil. When a modified proctor hammer and higher compaction energy (2,700 kNm/m^3) were used, the CBR values increased up to 16.79 after 10, 30, and 65 blows.

Most past studies have determined the collapse potential based on the odometer test. However, the small size of the test odometer test specimen (diameter of 50 to 70 mm and height of 20 mm) may lead to less accurate results when applying different improvement methods. In this study, an experimental testing program was conducted by utilizing a laboratory footing model to evaluate the collapsibility of gypseous soil that was improved by the compaction technique and by adding water treatment sludge.

2. MATERIALS AND METHODS

2.1 Soil

The soil used in this study was obtained from the campus of the University of Anbar in the Al-Anbar Governorate, west of Iraq. This location was chosen because of the cracks observed in the building, walls, and ceilings caused by the collapse phenomena of the existing gypseous soil. The soil sample was collected from a depth between 1 to 1.5 m. According to the visual identification, the model is a light brown fine to medium sand with some fine gravel and a significant amount 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.

Table 1: Physical and chemical properties of the used soil.

Test	Quantity	Standard
Water Content %	6.6	[14]
Specific Gravity, Gs (by Kerosene)	2.45	[15]
Maximum Dry density MDD, g/cm^3	1.625	[16]
Minimum Dry density, g/cm^3	0.943	[17]
Average Dry density, g/cm^3	1.284	-
In Field Density, g/cm^3	1.25	[18]
Optimum Moisture Content, OMC%	15	[16]
Void ratio in the field, e	0.96	-
Void ratio, e_{max}	1.62	-
Void ratio, e_{min}	0.51	-
Porosity in field, n	0.487	-
Degree of saturation in field,	17.02	-
Passing sieve (0.075mm) %	3.58	[19]
Organic matter, O.M %	3.78	[20]
SO_3 acid (Sulfuric acid) %	17.2	[21]
Total soluble salts, TSS %	20	
Gypsum Content (Using SO_3 Methods)	37	
pH	7.7	[22]

2.2 Sludge

In this study, a new technique is suggested to recycle sludge produced from drinking water treatment by utilizing it to reduce the collapsibility of gypseous soils. The sludge was obtained from the site of the Great Ramadi Water Project. The physical properties of the sludge are listed in Table 2. The chemical composition was determined using X-ray Fluorescence XRF, as shown in Table 3. The sludge was mixed with the soil at 10%, 15%, and 20% by the weight of the soil.

Table 2: The properties of the sludge from drinking water treatment.

Test	Quantity	Standard of the test
Water content %	1.55	[14]
Liquid limit % Plasticity index %	59.44 17.83	[23]
Specific gravity, G_s	2.58	[15]
Organic matter, OM %	1.81	[20]
pH	7.6	[22]

Table 3: Chemical composition of the sludge.

sludge	SiO_2	Al_2O_3	CaO	Fe_2O_3	Na_2O	K_2O	MgO	MnO	SO_3
Percentage	6.843	0.811	16.521	0.091	0.412	0.943	0.301	0.085	0.341

2.3 Test Methods

The stabilized soil was subjected to the Standard Proctor Compaction Test. To improve the engineering characteristics of gypseous soils, the sludge was added at 10%, 15%, and 20% by the weight of the soil. The compaction tests were conducted following [16]. Figure 1 shows the curves obtained from the compaction testing of the untreated soil and the soil-sludge combinations. At 10% sludge concentration, the MDD of soil-sludge mixes increased considerably to 1.637 g/cm^3 because the fine-grained sludge acted as filler materials. However, as the sludge content increased to 20%, the MDD value was 2.77% less, and the optimum moisture content OMC% value was 4% higher than those for the samples with 0% sludge. Many earlier studies, like those by [24], had shown that when the sludge content increased, the MDD decreased, and the OMC increased. Due to the strong capacity of sludge to absorb more water required for hydration, the OMC increased when sludge concentration increased. This absorbed water will create more holes in the soil, decreasing the MDD values.

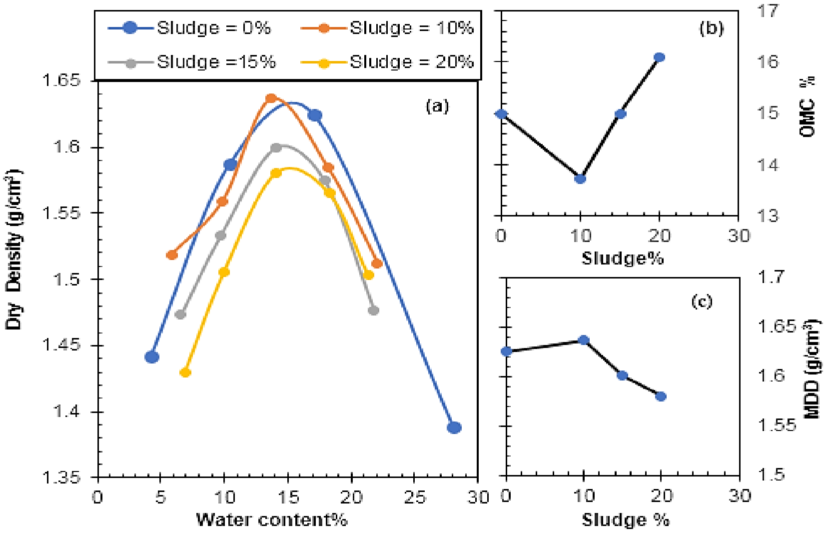

Figure 1: (a) The compaction curves for soil with various levels of sludge, (b) Variation of optimum water content with sludge content, and (c) Variation of maximum dry density with sludge content**.**

A single oedometer test was conducted to determine how adding sludge enhances collapsible gypseous soils. This test determined the optimum percentage of sludge necessary to be used in the laboratory model test. Several collapse experiments were performed on soil stabilized with different rates of sludge (10%, 15%, and 20%) after one day of curing. The procedure [25] was followed to conduct the test. The soil specimen was loaded with a load increment ratio of one to reach a vertical pressure of 200 kPa. The soil sample was soaked in water for 24 hours, after which additional pressure levels were added to get 400 kPa.

2.4 Laboratory Model Test

A laboratory model was manufactured to evaluate the gypseous soil's collapse potential with different treatment methods. Specifically, the collapse potential was determined for the soil layers below the model footing level placed at various thicknesses, relative densities, and sludge content values. The model consists of three main parts: 1) the box, 2) the footing, and 3) the loading frame, as shown in Figure 2. The box of the model is (600x600x600) mm and manufactured from a steel plate of 5 mm thickness to provide more rigidity and resist Horizontal displacement of the soil. The box is positioned on concrete blocks that should be balanced to keep the horizontal level of the base. The footing is composed of solid steel square and has dimensions of (100x100x6) mm. The footing model is also manufactured from thin steel plates positioned in the box's center. Loads are transmitted to the footing by a loading ram with a diameter of 40 mm and a length of 300 mm. This loading ram is connected with a free movement steel bar of 1200 length, 50 widths, and 100 mm height. Static loads are placed in the center of the steel bar. Two-dial gauges of 0.01 mm sensitivity are installed on the footing and screwed to the horizontal steel rod by a magnetic holder to measure the settlement of the footing. During the saturation phase, a constant head was provided by connecting the saturation tubes to two water tanks.

Figure 2: Details of the laboratory model.

The dry soil was placed in the box in seven layers, each of which was 50 mm thick, and compaction energy was used to achieve the approximate required relative density. A steel tamper of 5.8 kg was used to compact the layers. The placement of the soil layers was performed in the following:

a) The soil layer right below the footing level (top layer) was improved either by compaction to the MDD and OMC (without sludge) or by compaction (with sludge treatment). The thickness of this soil layer was 0, 50, and 100 mm, which represents 0, 0.5, and 1 time the width of the footing [B].
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 loading process started with an initial weight of 50 kg, equivalent to a stress of 49.05 kPa, and then increased by another 50 kg until it reached 200 kg, equal to a stress level of 196.2 kPa (about 200 kPa). Each load increment was kept until the dial gauge reading variation reached minimal values. A stress level of 196.2 kPa was applied and sustained for 24 hours before the soil was saturated for another 24 hours.

3. RESULTS AND DISCUSSION

3.1 Collapse Potential from the Oedometer Apparatus

Figure 3 shows the variation of collapse potential with sludge content for the specimens prepared at the maximum dry density and optimum water content obtained from the compaction tests. The results show that adding sludge by 10, 15, and 20% decreased the collapse potential by 50, 31, and 18%, respectively. This decrease in the collapse is attributed to the bonding action of the sludge, which works as a filler that strengthens the soil structure, leading to a reduction in the deformation upon wetting.

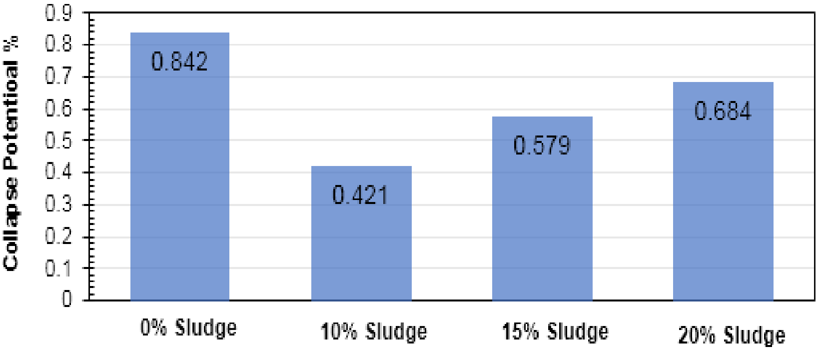

Figure 3: Collapse potential variation with the percentage of sludge, as obtained from the odometer test.

3.2 Collapse Potential from the Laboratory Model

3.2.1 The Effect of Relative Density on the Collapse Potential

The collapse values (∆S) represent the change in the magnitude of collapse settlement (∆S) 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 ∆S values decreased. For the relative density of 51, 65, and 77%, the ∆S values were 45.65, 39.59, and 14.68 mm, respectively, as shown in Figure 4. According to [25] severity evaluation of the collapse potential, gypseous soil is classified as "very severe trouble" at the RD between 51 and 65% and as "trouble" at RD of 77%. An increase in soil stiffness and frictional forces may cause this.

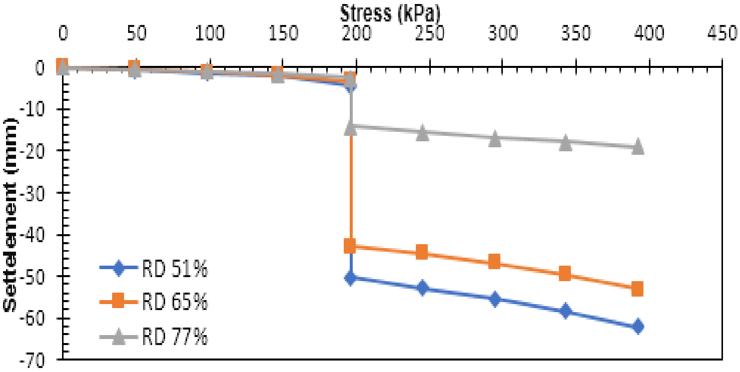

Figure 4: Collapse results at different relative density.

3.2.2 The Effect of Compaction Thickness on the Collapse Potential

To evaluate the effect of compaction (without sludge treatment) on the collapsibility, the model test was conducted at the same relative densities of 51, 65, and 77%, replacing the top layer with soil compacted to the MDD and OMC. The observations below are for the soil that was compacted to 0B, 0.5B, and 1B thicknesses:

1) It is clear from Figure 5, which shows the outcomes of the laboratory work model that the change in collapse settlement (∆S) decreases by 45.65, 40.789, and 11.97mm as the compaction depth thickness under the foundation increases. Based on the severity classification of the collapse potential mentioned in [25], the classification of the gypseous soil is "severe" at 52% RD.
2) From Figure 6, which shows the laboratory work model outcomes, the change in collapse settlement (∆S) decreases by 39.59, 9.89, and 5.57mm as the compaction depth thickness under the foundation increases. Based on the severity classification of the collapse potential, the classification of the gypseous soil changed from "severe" when (0 B) to "moderately severe" when (0.5 B) to "moderate" when (1 B) at 65% RD.
3) From Figure 7, which shows the results of the laboratory model, the change in collapse settlement (∆S) decreased by 14.68, 4.8, and 4.04 mm as the compaction depth thickness under the foundation increased. Based on the severity classification of the collapse potential, the classification of the gypseous soil changed from "severe" when (0 B) to "moderate" when (0.5 and 1B) at 77% RD.

According to [26], the collapsibility settlement reduction factor (CSRF) is used in the following formula to compare the collapse test results before and after utilizing various treatment methods, as shown in Figure 8.

$$\mathrm{CSRF} = \left(1 - \frac{\Delta \mathrm{St}}{\Delta \mathrm{Su}}\right) \times 100 \tag{1}$$

ΔS_t = Model of treated soil settlement change.
ΔS_u = model of untreated soil settlement change.

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. Moreover, the collapse values from relative density RD 65% best represent the field density. The compaction thickness of 0.5B is the most cost-effective thickness of the layer. For the compaction treatment, similar behavior was observed by [27]. Therefore, one of the most practical and successful strategies to increase soil resistance against collapse is the compaction of the top layer under the foundation.

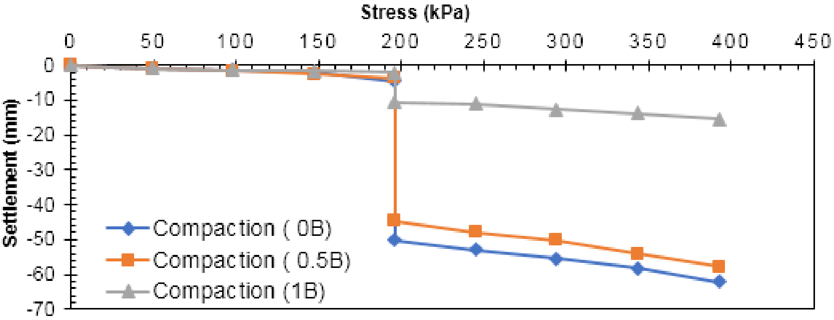

Figure 5: Collapse results for the soil with RD=51%.

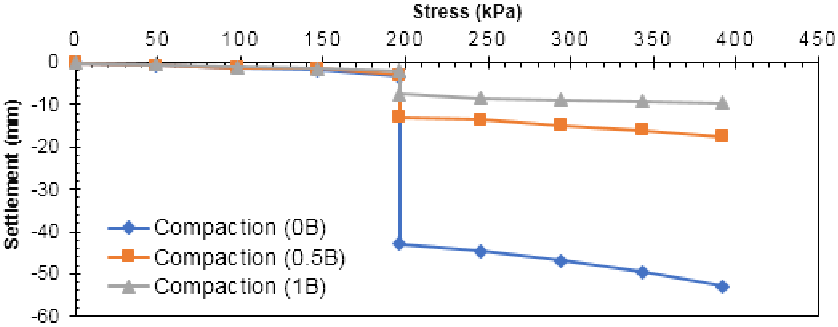

Figure 6: Collapse results for the soil with RD=65%.

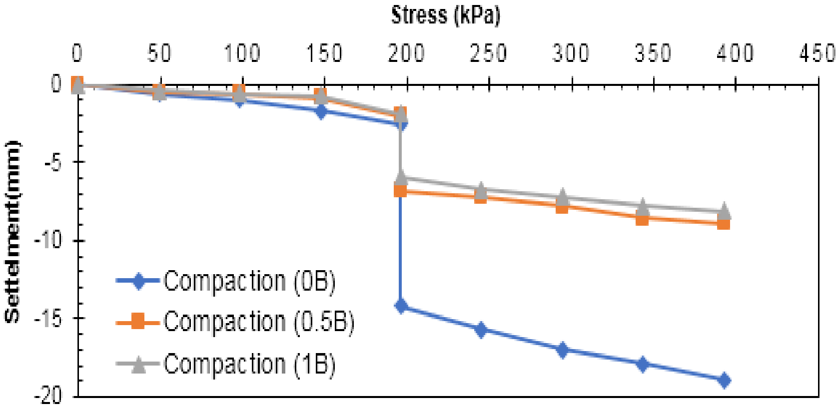

Figure 7: Collapse results for the soil with RD=77%.

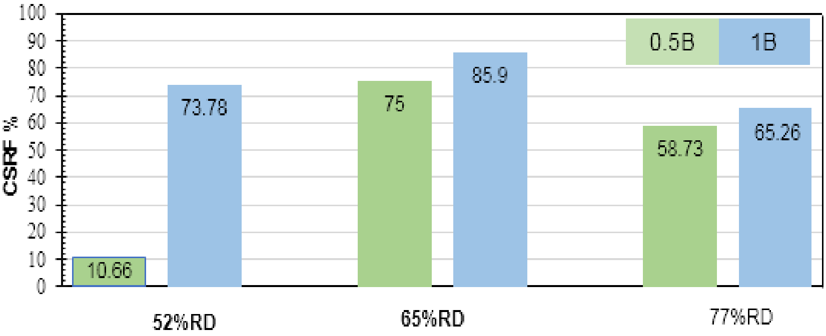

Figure 8: CSRF-RD.

3.2.3 The Effect of Sludge Treatment

As concluded from the previously presented results, the best results were obtained from the tests with a compacted layer of 0.5B and a RD of 65%. Therefore, the sludge was used to improve the soil further. The preparation procedure consists of two main steps: first, the soil was compacted at dry unit weight, and second, a layer of stabilized soil with a percentage of sludge (10%) at one day of curing at room temperature was spread over the first layer. The results of the model test with compaction treatment and sludge at a relative density of 65% are shown in Figure 9. Moreover, these data show that the collapse settlement (ΔS) values decreased from 9.89 mm without treatment to 5.47 mm with treatment by sludge. The total thickness layer (350 mm) under the foundation was classified as "moderately severe" when (0.5 B) and "moderate" when (0.5 B with 10% sludge) at 65% RD based on the severity rating of the collapse potential indicated in [25].

The CSRF values for the sludge-treated soil at 05B are shown in Figure 10. According to these results, the maximum value of the CSRF reaches 86.18% when using the treatment with compaction and sludge. It was obvious that adding sludge enhanced gypseous soil's behavior. Adding sludge may fill any voids developed from the gypsum dissolution process, leading to decreased collapse. These findings are in agreement with those obtained by [28].

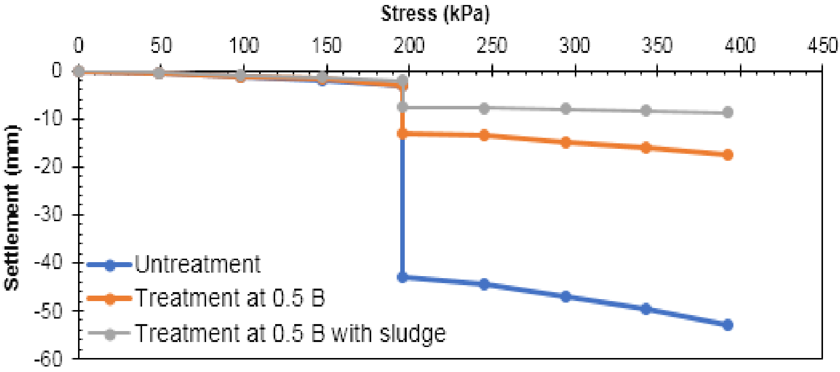

Figure 9: Collapse results after sludge treatment at 0.5B and 65% RD.

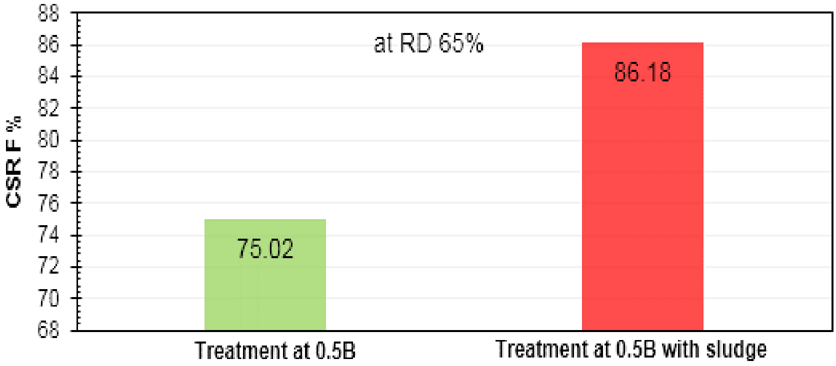

Figure 10: Increase in the CSRF values after sludge treatment at 0.5B.

4. CONCLUSIONS

This study evaluated the effect of compaction and sludge on the collapse characteristics of gypseous soil. The developed laboratory model was used to determine the collapse potential for the applied improvement method. Based on the test results, the following conclusions were reached:

- Increasing the relative density highly decreased the collapse potential for all the conducted tests.
- The collapse potential decreased as the thickness of the top layer, compacted to the MDD, increased for all the RD values.
- The improvement procedure at RD of 65% and compaction thickness of 0.5B is recommended for the gypseous soil investigated in this study.
- The water treatment sludge decreased the collapse potential with the compacted layer below the footing.
- The collapsibility settlement reduction factor was 75 % the top compacted layer of 0.5B (50 mm thickness) was used.
- The collapsibility settlement reduction factor was as high as 86% when the sludge was used in the top layer of 0.5B.
- By using the laboratory model, additional tests are required to evaluate the effect of leaching on the collapsibility of the improved gypseous soil.

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