

Compressibility and Strength of Natural and Steel Slag Treated Gypseous Soil

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ABSTRACT

Significant portions of the Earth's surface are covered with soils, and when they eventually get saturated with water, they may experience significant changes in volume. These materials are called collapsible soils. Gypsum rocks are formed as a result of the evaporation of salt water from lakes formed in desert or semi-desert areas. The implication of steel slag as a modifier on the compressibility and shear strength of gypseous soil was investigated in this work. Samples of soil with a 53.36% gypsum concentration were acquired from Tikrit, located in the Salahaldeen province of Iraq. Steel slag was added in proportions of 3%, 6%, 9%, 12%, and 15% by weight of the soil. Collapse and direct shear tests were conducted for both natural and treated samples. According to the research findings, the treated soil has significantly higher degree of cohesion and an angle of internal friction, and the Collapse Potential (CP) value has substantially dropped. This enhancement can reach up to 69.28% at 15% treatment for collapse potential, which represents the best weight ratio for the additive. The cohesion and angle of internal friction increased to 155.41% and 82.0%, respectively, with 15% treatment for the direct shear test.

Keywords-gypseous soil; steel slag; collapsibility reduction factor; soil strength; cohesion increasing factor; friction angle increasing factor

I. INTRODUCTION

Collapsible soil refers to soil that is strong in its natural dry state but suffers from decomposition and large volumetric changes when water reaches it. Collapsible soil can be defined in another way as soil whose total volume decreases when water reaches it, resulting in a subsidence in the surface of the earth. Gypseous soils are examples of such soils and are found in semiarid and arid regions around the world. Multiple types of problematic soils exist, one of which is the collapsible gypseous soil [1]. This issue has drawn the attention of many researchers using different additives to improve the engineering properties of collapsible soils or at least mitigate their adverse effects. Modifying the characteristics of soil to enhance its engineering performance is known as soil stabilization.

Strength, compressibility, and plasticity necessitate the greatest modification. Authors in [2] explored how the characteristics of gypseous soils were affected by the use of aqueous calcium chloride ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$). Following the soaking in a 20% calcium chloride solution, samples demonstrated reduced collapsibility, hydraulic conductivity, gypsum disintegration, and leaching. Authors in [3] concluded that the unconfined compressive strength increases to 33% at 6% of liquid asphalt and then decrease with an increase in asphalt ratio.

Authors in [4] chose clinker material for use with cement in order to examine its effects on the properties of gypseous soil containing 40% gypsum. The findings demonstrated that applying 4% clinker to the soil optimized its shear strength parameters while significantly reducing its collapse potential.

Authors in [5] assessed how the engineering properties of gypseous soil were affected by a combination of sand dunes and emulsified asphalt. It was revealed that incorporating a mixture of 9% sand dunes and 6% emulsified asphalt enhanced the cohesion and angle of internal friction. Authors in [6] examined the effects of three separate additives—xanthan gum, cutback, and silica fume—on the distinct characteristics of gypseous soils with varying gypsum contents. According to the results, adding 10% silica fume generated the maximum cohesion and the lowest collapse potential. A percentage of 7.5% yielded the highest cohesive value for xanthan gum, while a ratio of 2.5% yielded the lowest CP value. The cohesion value was highest when the cutback was 6%, and the CP value was lowest when it was 8%. Authors in [7] investigated how silica fume and lime affected the physical characteristics of gypseous soil after being exposed to water for 24 hours, 7 days, and 28 days. By incorporating 1% of these materials, the unconfined compressive strength was shown to have increased by fifteen folds. When silica and lime were used simultaneously, the gypseous soil's engineering properties were enhanced.

Authors in [8] explored the effects of silica fume and nano silica fume on the physical properties of gypseous soils. In [9], the effects of introducing petroleum compounds to gypseous soils were investigated. Both natural and cement-treated gypseous soils' collapsibility was examined in [10] in relation to the initial water content. It has been demonstrated that lowering the starting amount of water minimizes the collapse potential. In both naturally occurring gypseous soils and those treated with 5% cement, keeping the initial level of water between 15% and 20% during construction lowers the chance of abrupt collapse upon subsequent saturation. The collapse potential of gypseous soil was considerably decreased by adding silica fume and lime, with silica fume being more effective [1]. According to the authors in [11], polypropylene fibers (PPF) are more successful than sugarcane fibers (SCF) at altering the inherent characteristics of gypseous soils, even though both can be used.

Millions of tons of wastes are produced from industrial plants. These wastes' disposal becomes one of the most important problems in the world. One of the methods of waste disposal is to use these materials for soil improvement. A residual product of the manufacturing process of steel is steel slag. Incorporating complex silicates and oxides, it is a molten liquid that hardens when cooled. With the expansion of the construction sector, steel slag has found widespread use in applications such as soil stabilization. Steel slag has high bearing capacity and valuable wear resistance [12]. Applying 20% fine steel slag decreased the plasticity index and free swell of high plastic subgrade soil, according to data presented by the authors in [13]. By adding 20% fine steel slag, the unconfined compressive strength, maximum dry density, and California Bearing Ratio (CBR) were also greatly improved. According to the authors in [14], adding steel slag and lime can increase the density and compaction performance of stabilized sandy soil. Author in [15] discovered that using steel slag improves the treated soil's bearing ability. Adding steel slag also increases the shear strength, dynamic modulus, and angle of internal friction [16].

Prior research has concentrated on enhancing the qualities of gypseous soil with traditional chemical enhancements which included clinker, cement, and lime. The scientific study on the shear strength and compressibility of sandy gypseous soils utilizing steel slag is conspicuously far from complete. By investigating the effects of adding steel slag, another byproduct of the steel industry, as a sustainable and efficient alternative for treating gypsum soil, the current study seeks to close this gap and offer a cost-effective solution to the engineering features of gypseous soils, specifically the parameters of shear strength and collapsibility.

II. MATERIAL PROPERTIES

A. Description of Soil

Originating from Tikrit city in the Salahaldeen governorate of Iraq, the gypseous soil employed in this study had a gypsum percentage of 53.16%. The soil has been categorized as poorly graded sand (SP) by the accounted for soil classification system (USCS). The physical qualities of the soil, as measured by the procedures suggested in [17, 18], are shown in Table I. Figure 1 displays the soil's particle curve's size distribution. Table II summarizes the outcome of the chemical tests conducted on the soil.

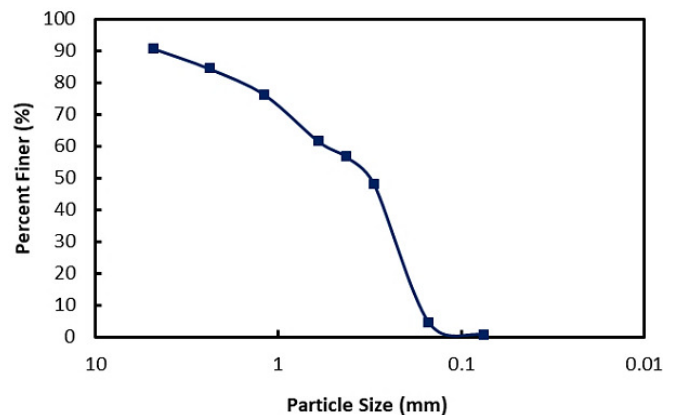


Fig. 1. The distribution of the used soil's grain sizes.

TABLE I. CHARACTERISTICS OF THE UTILIZED SOILS

Index property	Value
Soil classification according to USCS	SP
Coefficient of uniformity (C_u)	3.47
Coefficient of curvature (C_c)	0.48
Field dry unit weight (kN/m^3)	15.21
Natural field water content (%)	5.81
Liquid Limit (LL) (%)	16.2
Plastic Limit (PL) (%)	N.P.
Specific Gravity (G_s)	2.51
Standard maximum dry unit weight (kN/m^3)	18.1
Optimum Moisture Content (%)	14.0
Angle of friction (ϕ) ($^\circ$)	13.4
Cohesion (c) (kN/m^2)	1.57
Collapse potential (C_p)	6.77

TABLE II. UTILIZED SOILS' CHEMICAL CHARACTERISTICS

Index property	Value
Total soluble salts (%)	61.17
Gypsum content (%)	53.36
Organic matter (%)	0.08
PH	7.9

B. Description of Steel Slag

The current investigation utilized steel slag, a waste product of the Bazin district steel factory in the Sulaymaniyah province in Iraq, which had a specific gravity of 3.39. After being manually crushed, the slag was sieved using sieve No. 60. Table III illustrates the chemical composition of the used steel slag.

TABLE III. ASPECTS OF THE USED STEEL SLAG'S CHEMICAL COMPOSITION

Chemical composition	Percentage (%)
Magnesium Oxide (MgO)	2.08
Silica, amorphous (SiO ₂)	14.24
Ferri Oxide (Fe ₂ O ₃)	42.01
Aluminum Oxide(Al ₂ O ₃)	2.81
Calcium Oxide (CaO)	32.96
Others	5.87

III. COLLAPSIBILITY TESTS

In [19], the process for assessing the soil's CP is pointed out. The collapse potential of a disrupted soil specimen can be ascertained by reforming it in a consolidation ring at its original moisture percentage. The specimen is subjected to step loads up to 200 kN/m² of pressure. After being inundated to saturation, the specimen is kept at this pressure for a full day. The void ratios (*e*₁ and *e*₂) prior to and thereafter inundation will be determined through this test. Thus, the most crucial formula for calculating CP is:

$$C_p = \frac{e_1 - e_2}{1 + e_0} \quad (1)$$

where *e*₀ = natural void ratio, and *e*₁ and *e*₂ are the void ratios before and after soaking, respectively.

The CP has been correlated with foundation challenges associated with collapsing soils. These relationships are outlined in Table IV and summarized in [20].

TABLE IV. SEVERITY OF FOUNDATION ISSUES AND POSSIBILITY OF COLLAPSE (FOLLOWING [20])

C _p (%)	Severity of problem
0 – 1	No problem
1 – 5	Moderate trouble
5 – 10	Trouble
10 – 20	Severe trouble
> 20	Very severe trouble

IV. RESULTS AND DISCUSSION

A. Compressibility Characteristic (Collapse Test)

Based on the results of the collapse test, Table V presents the CP values for natural soil and gypseous soil treated with

steel slag. Values of the Collapsibility Reduction Factor (CRF) are also included, which can be calculated using:

$$CRF (\%) = \left(1 - \frac{C_p (\text{Treated soil})}{C_p (\text{Natural soil})}\right) \times 100 \quad (2)$$

Figure 2 displays the final collapse test results for both treated and natural soils containing varying amounts of steel slag. It was found that CP drastically decrease as the percentage of steel slag increased, a trend which is quite evident in Figure 3. The reason for this phenomenon is that the volume of soil voids decreased as the amount of steel slag in the soil is increased, filling these empty spaces. Furthermore, due to its inherent qualities, the steel slag improved the inter-cluster bonding force, which in turn reduced the gypseous soil's collapse potential. According to the classification proposed in [20], the CP value decreased from 6.77 (problem) to 2.08 (moderate trouble). The implications of steel slag intensity on the CRF are depicted in Figure 4. Higher steel slag content is found to enhance the CRF, which approaches the lowest possible value of 69.28% at 15% steel slag. Consequently, the shear strength values of the injected soils were considerably affected by the inclusion of the ingredient [21].

TABLE V. CP VALUES AND CRF FOR NATURAL AND TREATED SOIL

Steel slag (%)	C _p (%)	CRF (%)
0	6.77	0
3	4.95	26.88
6	3.49	48.45
9	2.97	56.13
12	2.29	66.17
15	2.08	69.28

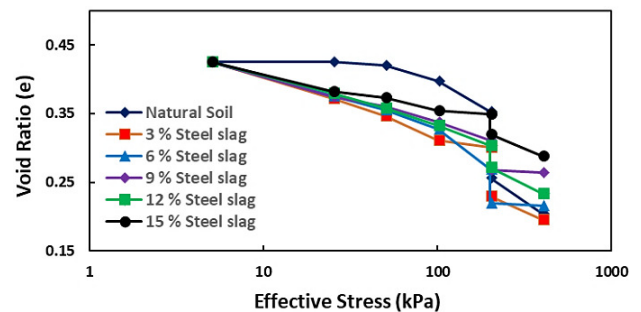


Fig. 2. Collapse test results for soil treated with steel slag and natural soil.

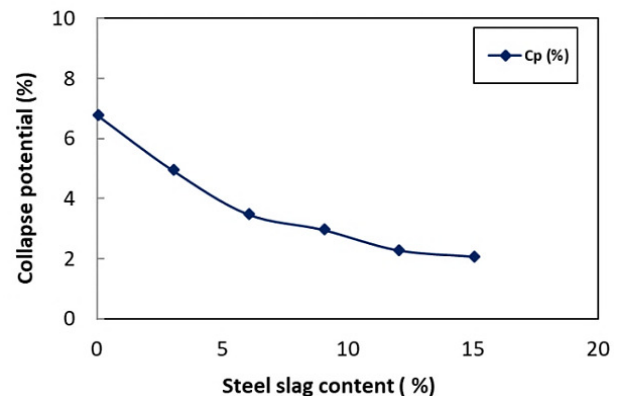


Fig. 3. CP variation with steel slag content (%).

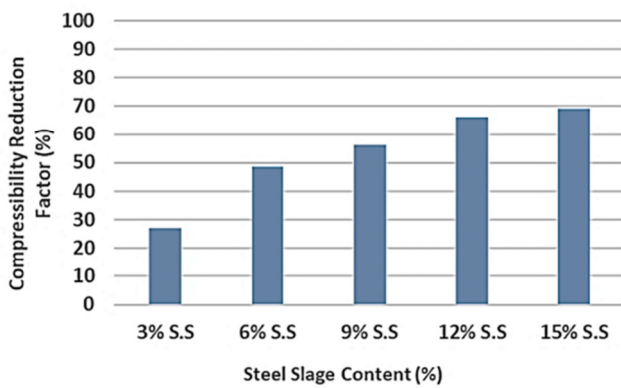


Fig. 4. CRF variation with steel slag content (%).

B. Strength Characteristic (Direct Shear Test)

Table VI and Figure 5 give the findings of the direct shear experiment for semi-dry natural and steel slag-treated soil (natural moisture content: 5.81%, field dry unit weight: 15.21 kN/m³). The relationship that exists between the angle of internal friction (ϕ) and the quantity of steel slag and cohesiveness (c) is further illustrated in Figure 6. As the percentage of steel slag grows, it is evident that the angle of internal friction (ϕ) rises. However, the rate of cohesion improvement is slower than the friction angle. The angular and abrasive particles of steel slag generate a growing friction angle, which is the primary cause of this behavior.

TABLE VI. SHEAR STRENGTH PARAMETER VALUES FOR NATURAL AND TREATED SOIL

Steel slag (%)	Cohesion (c) (kN/m ²)	Angle of internal friction (ϕ) (°)
0	1.57	13.4
3	1.58	14.39
6	1.61	15.6
9	1.97	19.28
12	2.43	22.17
15	4.01	24.39

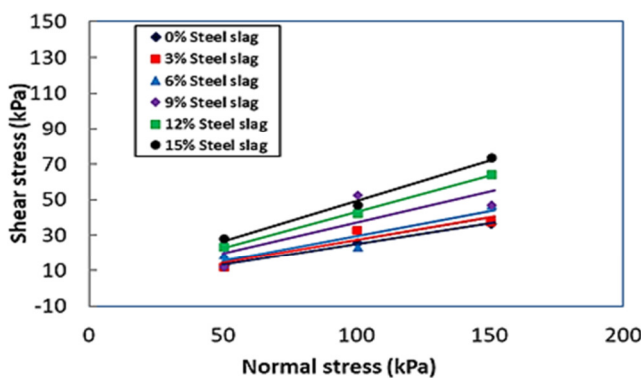


Fig. 5. Direct shear test results for soil treated with steel slag and natural soil.

Table VII and Figure 7 show the variation of the Cohesion Increasing Factor (CIF) and Friction Angle Increasing Factor (FAIF) with steel slag content, respectively. CIF and FAIF can be obtained from:

$$CIF (\%) = \left(\frac{c (Treated\ soil)}{c (Natural\ soil)} - 1 \right) \times 100 \quad (3)$$

$$FAIF (\%) = \left(\frac{\phi (Treated\ soil)}{\phi (Natural\ soil)} - 1 \right) \times 100 \quad (4)$$

Both FAIF and CIF have increased, but generally speaking, FAIF has increased at a faster rate than CIF. The functioning of steel slag, which has great wear resistance and frictional qualities, is responsible for this matter. Furthermore, steel slag has a larger specific gravity than soil particles, thereby enhancing its strength against shear and stress resistance.

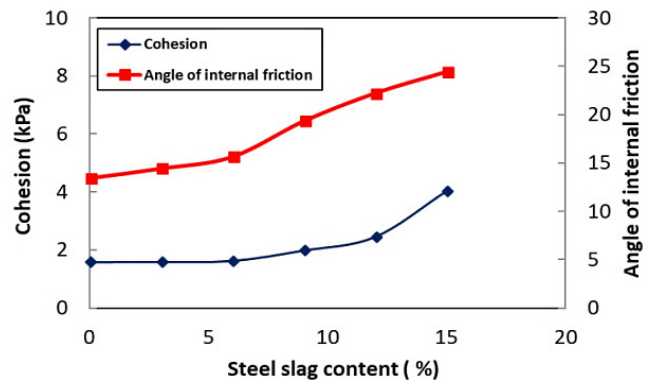


Fig. 6. Cohesion and internal friction angle variation as a function of steel slag content.

TABLE VII. STRENGTH INCREASING FACTORS FOR NATURAL AND TREATED SOIL

Steel slag (%)	CIF (%)	FAIF (%)
0	0	0
3	0.64	7.39
6	2.55	16.42
9	25.48	43.89
12	54.97	65.45
15	155.41	82.0

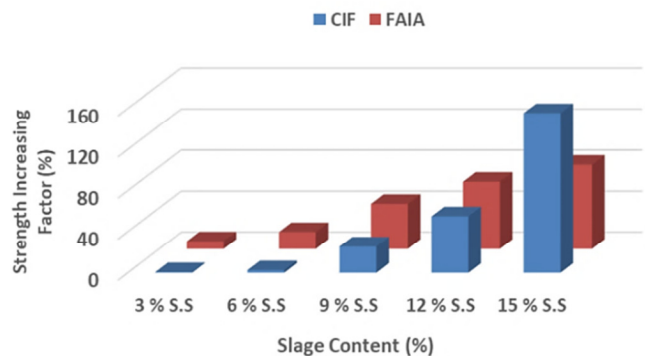


Fig. 7. Variation of CIF and FAIF with steel slag content.

Authors in [22] looked into using steel slag as mulch to enhance the inherent characteristics of clayey soil. The results of the experiments showed that when the amount of steel slag in the soil rose, the angle of internal friction increased and the dry density, plasticity, expansion possibility, and cohesion interception reduced. No previous studies have specifically examined the effect of steel slag on the compressibility and

shear strength parameters of sandy gypseous soils, making direct comparisons with existing research unfeasible. Accordingly, this study provides new insights into the behavior of sandy gypseous soils enhanced with steel slag, filling an important research gap and providing valuable data for future geotechnical applications.

V. CONCLUSIONS

To ameliorate the qualities of sandy gypseous soil, steel slag was applied in this study. It came to light that applying steel slag to gypseous soil reduced its compressibility. It was shown that when the amount of steel slag increases, the Collapse Potential (CP) decreases. For gypseous soil treated with steel slag, the Collapsibility Reduction Factor (CRF) rises to over 69% at 15% steel slag content. Furthermore, gypseous soil's strength characteristics are enhanced by adding more steel slag. The more of the steel slag there is, the higher the shear strength parameters (ϕ and c). The rate of increase in the angle of internal friction was more than that of cohesion. Cohesion Increasing Factor (CIF) and Friction Angle Increasing Factor (FAIF) for gypseous soil treated with steel slag reached about 155% and 82.0% for 15% steel slag content. Therefore, it is possible to effectively enhance the collapsibility characteristics of gypseous soils by adding 12% steel slag. Beyond this ratio, further improvement is negligible. Finally, it was found that gypseous soil's shear strength increases gradually with an increase in steel slag concentration.

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