Enhancing the Engineering Properties of Gypseous Soil Utilizing Fly Ash

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ABSTRACT

Collapsible soils are robust in their natural, dry state but exposure to water leads to decomposition. They also undergo large volumetric changes often associated with the detachment of the ground surface. The construction on such type of soils is challenging duet to their costly need for treatment. Gypseous soil is considered one of the important collapsible soils and is typically found in desert and semi-arid areas with widespread moisture deficits. This study investigates the effect of fly ash as an amendment on the compressibility and shear strength of gypseous soil. A 51.23% of gypsum content is found in the soil samples collected from the city of Tikrit in the Salah al-Din governorate of Iraq. Fly ash is added at percentages of 4, 8, 12, 16, and 20% of the soil's weight. Direct shear and collapse laboratory tests are executed on both natural and treated soil. The findings demonstrated that the treated soil exhibited a significant increase in both cohesion and the angle of internal friction, and a decreased value of the Collapse Potential (CP). The collapsibility can be limited to 55.29% with a 20% addition of fly ash. The cohesion and internal friction angle are improved by 53.48% and 81.47%, respectively. Finally, the ideal percentage of fly ash ranges between 12% and 16%, as the enhancing ratio for both the collapse and the soil's shear strength significantly decreases beyond this percentage.

Keywords-gypseous soil; fly ash; collapse; collapse enhancing ratio; soil strength; strength enhancing ratio

I. INTRODUCTION

Collapsible soils can withstand applied stress in their natural state without significant subsidence, provided that the moisture content is not excessive. In that case, significant subsidence will occur leading to problems on the structures constructed on such type of soils. The severity and intensity of the collapse depend on many factors, such as the soil-forming materials, soil particle shape, particle size distribution, soil void formation, ion concentration, and binding materials, which may include gypsum, calcium carbonate, salts, iron oxides, and clayey materials.

Similarly, gypseous soils generally demonstrate rigidity in the dry state. However, fluctuations in water due to the shifts in their water table level or water absorption can impact these soils. This can lead to a decay of the gypsum, which in turn can create fissures and voids that make gypsum soils more permeable [1]. Due to the lower pressure exerted by water when compared to the air pressure in the pores of the soil, these types of soils undergo more than two distinct phases when not fully immersed in water. This behavior poses a significant geotechnical issue. Such reduction can lead to localized and significant stresses, volumetric amendments, and a diminution in the soil's shear strength. Water can reduce the adhesiveness of the soil particles, and therefore lead to an increased compactness of the soil. Additionally, the desaturation of the soil at the surface level can occur when there is negative pore-water pressure during dry conditions [2, 3].

Altering the characteristics of the soil can enhance its engineering performance, and is known as soil stabilization [4]. Strength, compressibility, and plasticity require the most changes. Authors in [5] applied calcium chloride or cement to gypseous soil. Their findings suggested that the gypseous soil's collapse coefficient dropped by 65% and its cohesiveness increased by 50% when cement was added. The cohesion was increased to more than 70% and the collapse coefficient was decreased to more than 70% by adding calcium chloride. Authors in [6] investigated the impact of petroleum products, such as kerosene, fuel oil, and engine oil, on gypseous soils. The direct shear test, both in the dry and soaked sample, revealed that adding engine and fuel oil to the soil enhanced its bonding capacity and angle of internal friction. Conversely, introducing kerosene to the soils led to decreased strength between the bonds of the particles and increased the angle of internal friction.

To further enhance the soil's physical and mechanical attributes, authors in [7] blended waste cement dust with gypseous soils with different gypseous contents acquired from two separate areas in Al-Najaf city. A 15% increase in additives boosted the coherence of the treated soil and decreased the pronounced internal friction angle in comparison to the original gypseous soil. Placing a 9% ceramic waste shallow foundation set on gypsum soil led to a raised soil bearing capacity and eliminated the adverse consequences of sinking and water [8].

Authors in [9] inquired about the strength and durability of gypseous soil that had been administered with pectin biopolymer in both soaking wet and dry conditions. Results reveal that the shear capacity of gypseous soil treated with a pectin biopolymer improves until the fifth cycle, even when the soil is regularly wet and dried. From the next cycle until the 15th, the strength slightly declined and the enhanced samples' volumetric stability increased until the final cycle. Authors in [10] inquired about whether using a reed ash and lime mixture might enhance and stabilize soils that have stability problems. The findings demonstrated that increasing the ratio of reed ash to lime mixture leads to enhancement of both the unconfined compressive strength and maximum dry density. Once the strength was at its peak, it started to decline. Additionally, the strength of the remedied soil was significantly boosted by adding 5% lime and 7% reed ash. After 28 days of conditioning, the treated soil's compressive strength was over 10 times that of the control soil.

Authors in [11] researched the implications of nanoparticles (nano-clay and nano-metakaolin) on the resilience to shear and collapsibility of gypseous soils before and after soaking. The higher the concentration of nanoparticles in the gypseous soil is, the less likely it is to collapse. The resistance to shear expands as well with increasing nanomaterial intensity and treatment time. Authors in [12] looked at whether calcium carbide residue and linear alkyl benzene sulfonic acid could possibly be exploited for creating a geopolymer. The results showed improved coherence, collapsibility, and somewhat diminution of the internal friction angle.

Authors in [13] investigated the possibility of enhancing the final bearing capacity of foundations constructed on gypseous soil by using woven geotextiles. Adding geotextile reinforcement to soil leads to increased bearing capacity and lessens the gypseous soil settlement. The utilization of recycled plastic trash as a method of soil fortification was investigated in [14]. According to the results, adding plastic trash to gypseous soil improved its geotechnical qualities and decreased the sample collapse.

Earlier studies focused on strengthening the qualities of gypseous soil with typical additions including clinker, cement, nano-metakaolin, nano-clay, and geotextile reinforcement. Fly ash, an alkaline substance produced by burning coal in thermal power plants, is occasionally utilized in the cement, brick, building, road, and embankment industries [15]. There are numerous geotechnical uses for fly ash that can improve the physicochemical characteristics of soil over time. The main goal of this study is to figure out how fly ash, as an addition, alters the technical features of sandy gypseous soils, including the collapsibility and shear strength parameters.

II. CHARACTERISTIC ASPECTS

A. *Soil Properties*

In the present study, gypseous soil with a gypsum concentration of 51.23% is retrieved from Tikrit city in the Salahaldeen governorate of Iraq. The Universal Soil Classification System (USCS) categorized this soil as poorly graded sand. The soil's physical traits are ascertained in accordance with [16, 17]. The results are documented in Table I.

TABLE I. INDICATORS OF THE UTILIZED SOILS' CHARACTERISTICS

Soil Property	Value
Specific Gravity	2.50
CP	6.71
Liquid Limit (%)	15.8
USCS dsil classification	SP
Coefficient of curvature	1.13
Coefficient of uniformity	3.25
Plastic Limit (%)	N.P
Field dry unit weight (kN/m^3)	14.81
Natural field water content (%)	6.62
Standard maximum dry unit weight (kN/m^3)	17.89
Optimum Moisture Content (%)	13.7
Angle of friction (φ) (°)	22.24
Cohesion (c) (kN/m^2)	4.45
Gypsum content (%)	51.23
Organic matter (%)	0.09
PH of Hydrogen	7.8
Total solubale salts (%)	59.21

Figure 1 illustrates a grain size distribution curve for the soil.

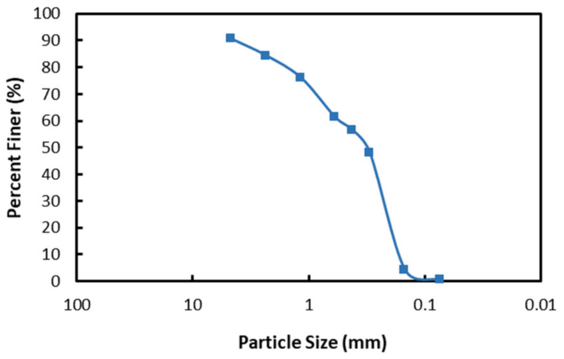

Fig. 1. Distribution curve of grain sizes in the used soil.

B. Fly Ash

In this investigation, fly ash class F is applied as a treatment additive to gypseous soil. The composition of the utilized fly ash is presented in Table II. All the samples are cured for 48 hours during which they are covered with layers of nylon and aluminum to ensure a stable water content in the samples.

TABLE II. CHEMICAL COMPOSITION OF FLY ASH

Chemical compound	**Percentage**
K_2O	1.296
Al_2O_3	18.273
CaO	3.145
LiO	14.87
Na_2O	0.683
MgO	1.191
TiO2	0.949
MnO	0.055
Fe_2O_3	7.288
P_2O_5	0.199
SiO_2	51.999
Sum	99.948

III. EXPERIMENTAL TESTS

A. Collapse Tests

Authors in [18] devised a strategy for assessing a soil's capacity to collapse. By placing an undisturbed soil sample in a consolidation ring with its original moisture content, the CP can be ascertained. Step loads are directed to the specimen up to a pressure of 200 kN/m^2. At this point, the specimen has been inundated to saturation and left for a whole day. The void ratios (e_1 and e_2) prior and following to overflow are obtained through this test. The CP is then attainable using:

$$C_P = \frac{e_1 - e_2}{1 + e_0} \qquad (1)$$

where e_o refers to the typical soil starting void ratio. The variables e_1 and e_2 are depicted in Figure 2, as proposed in [19].

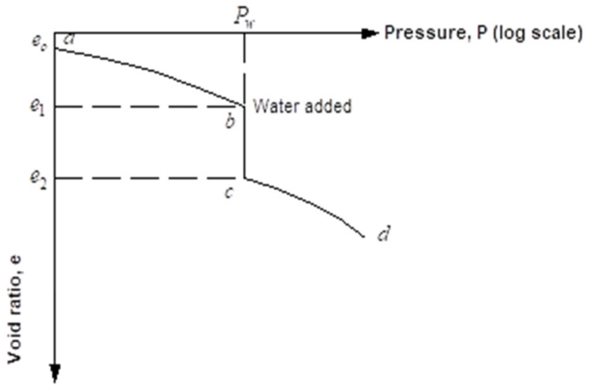

Fig. 2. Pressure-induced change in the void ratio for a collapsing soil.

The CP and the foundation complications related to a collapsing soil have been associated. These are listed in Table III and summarized by the authors in [20].

TABLE III. COMPLICATION INTENSITY PER CP PERCENTAGE

CP (%)	**Complication Intensity**
> 20	Critical
10 – 20	Severe
5 – 10	Moderate
1 – 5	Mild
0 – 1	Normal

B. Direct Shear Test

To determine the shear strength indicators for both the natural and fly ash-strengthened soils at field unit weight, the test indicated in [21] is conducted. Direct shear testing of soil samples is performed under semi-dry conditions.

IV. RESULTS AND DISCUSSION

A. Collapse Test Results

Following a collapse test, Table IV encompasses the CP and Collapse-Enhancing Ratio (CER) values for gypseous soil treated with fly ash and natural soil.

TABLE IV. CP AND CER FOR NATURAL AND FLY ASH-TREATED SOIL

Fly Ash (%)	**CP (%)**	**CER (%)**
0	6.71	0.00
4	6.51	2.98
8	5.36	20.12
12	4.10	38.90
16	3.33	50.37
20	3.00	55.29

The collapse test results for the treated and natural soil with different fly ash percentages are portrayed in Figure 3. As the concentration of fly ash increased, it was observed that the CP dramatically dropped, as also depicted in Figure 4.

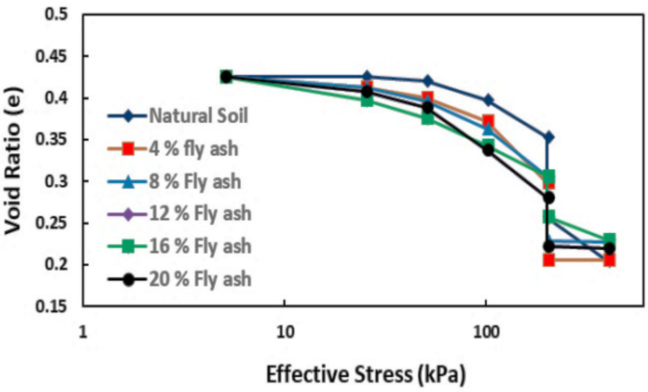

Fig. 3. Void ratio against effective stress of collapse test of natural and fly ash-treated soil for different percentages.

Fly ash is a soft, non-plastic material that contributes in filling the voids between the gypsum soil particles, improving the soil gradation and increasing its internal cohesion, thus being less susceptible to structural collapse. Additionally, the pozzolanic associations among fly ash, water, and the soil's calcium ions lead to the decrease in CER of gypseous soil treated with fly ash. Cementitious compounds (such as hydrated calcium silicates) originate as the outcome of these interactions, filling up gaps and enhancing the microstructure of the soil. As a result, collapsible porosity is reduced, and a more cohesive and stable structure is formed when the soil is exposed to moisture, reducing the soil's susceptibility to collapse upon re-saturation with water. This suggests that fly ash contributes to enhancing the overall stability of gypseous soils by reducing their structural fragility [15, 22, 23].

Gypsum is known to be water-soluble, and when present in large quantities in soils, it forms a brittle structure that collapses upon re-hydration. When fly ash is added, it can act as a partial barrier, preventing the rapid diffusion of water into the soil, thus slowing the rate of gypsum dissolution. This effect limits sudden volume changes and reduces the degree of collapse. According to the system of classification proposed in [20], the CP value decreased from 6.71 to 3.0 at 20% of the treatment. Figure 5 shows the fluctuation of the CER with the fly ash concentration.

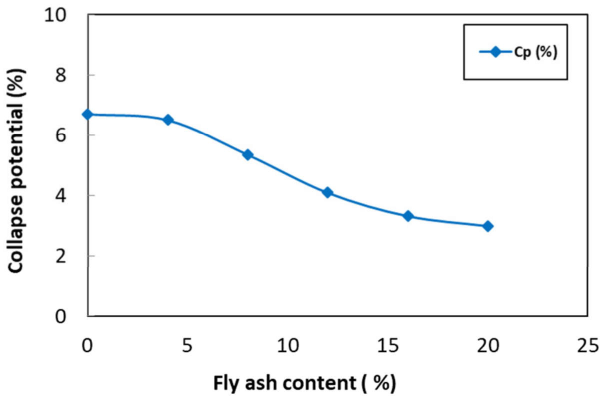

Fig. 4. Fly ash concentration agaisnt CP.

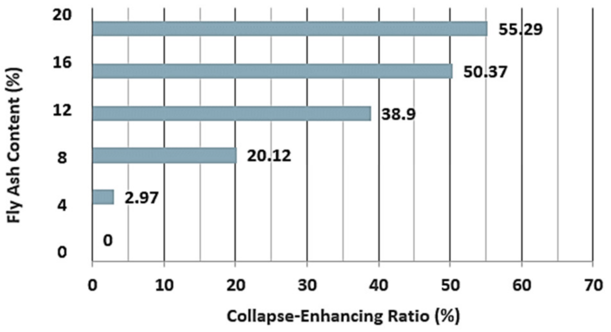

Fig. 5. Fly ash concentration against CER.

B. Direct Shear Test

The direct shear analysis conclusions for both naturally existing and fly ash-treated soil are shown in Table V and Figure 6 at the original level of water and field dry unit weight. The consequence of the fly ash concentrate on *c* and *φ* is illustrated more clearly in Figure 7. As the amount of fly ash went up, both these variables greatly expanded.

The pozzolanic reactions amongst the fly ash's free silica, water, and the partially dissolved calcium oxides from the gypsum allow the cohesion value to rise. These responses result in the emergence of compounds, such C-S-H, which serve as binding compounds amongst soil particles. Furthermore, the fine fly ash particles improve the internal cohesion and increase the soil's shear strength by plugging in gaps that exist between the soil particles.

TABLE V. DIRECT SHEAR TEST RESULTS

Fly ash (%)	*φ* (°)	*c* (kN/m^2)
0	22.4	4.45
4	35.37	5.33
8	36.61	5.93
12	39.35	6.67
16	39.95	6.72
20	40.36	6.83

Improving the soil's internal texture leads to an increase of *φ*. Internal reactions that lead to hardening also enhance the roughness of the interfaces, which subsequently enhances the internal friction. Additionally, greater soil density and fewer voids contribute to an improved frictional shear resistance.

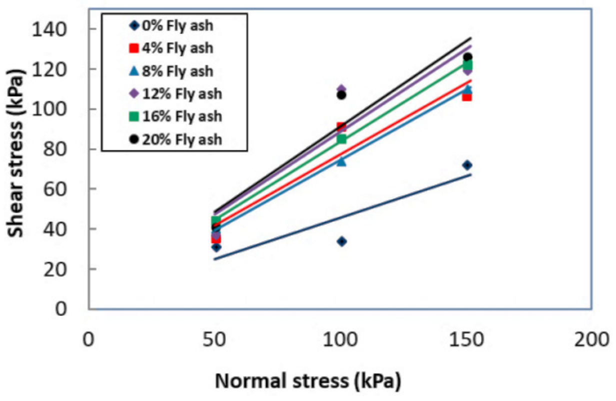

Fig. 6. Direct shear test across both natural and fly ash treated soil at different fly ash percentages.

TABLE VI. SER FOR NATURAL AND FLY-ASH TREATED SOIL

Fly ash (%)	SER (%)	
	φ (%)	*c* (%)
0	0	0
4	59.04	19.73
8	64.61	33.26
12	76.93	49.87
16	79.63	51.01
20	81.47	53.48

The enhancement in the *φ* is greater than that in *c* given the fact that the field moisture content is utilized during compaction. Fly ash's ability to improve *c* is diminished as a result of the incomplete pozzolanic reactions brought on by the lower moisture content.

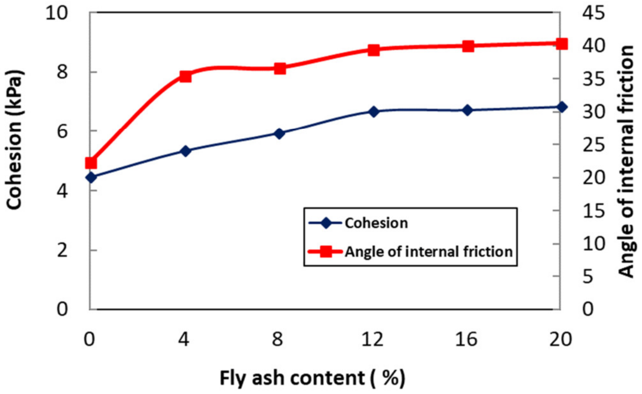

Fig. 7. Fly ash content agaisnt c and φ.

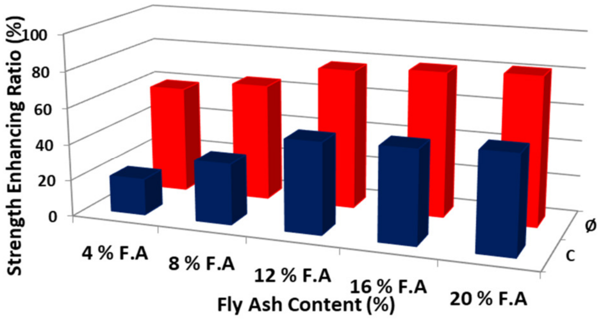

Fig. 8. SER variation against fly ash content.

V. CONCLUSIONS

The study results suggest that adding fly ash to gypseous soil significantly improves the soil's engineering properties, particularly in terms of the Collapse Potential (CP) and shear strength. An increase in fly ash concentration leads to a decrease in CP. Specifically, at 20% fly ash concentration the CP decrease exceeded 55%. Additionally, the results demonstrated that the shear strength coefficients, cohesion (c), and angle of internal friction (φ) were improved by enhancing the fly ash concentration.

However, due to altering the internal structure and particle distribution, the enhancement of φ was more noticeable than the improvement in c. The improvement in c exceeded 50%, while in φ it reached more than 80%. Concentrations between 12% and 16% of fly ash are particularly effective in improving compressibility and increasing the shear strength, presenting a practical and economical option for optimizing the gypsum soil in engineering applications.

Unlike most previous studies, this work focused on stabilizing clayey soils using fly ash to improve the properties of gypseous soils. Future work will focus on evaluating the long-term durability of fly ash-treated soils under environmental conditions, such as wet-dry cycles.

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