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Influence of Fine Materials on the Mechanical Behaviour of Treated Gypseous Soils under Unconfined Compression

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ABSTRACT

Gypsum soils in Iraq suffer from serious problems related to collapse and poor stability when exposed to moisture, which over time leads to subsidence and cracking of structures. This is one of the most prominent geotechnical challenges facing infrastructure projects in areas where these soils are common. This research aims to study the unconfined compressive strength (UCS) of gypsum soils using three main stabilizing agents: 8% fly ash, 4% silica fume, and 2% nano-silica fume, along with varying ratios of fine particles (10, 20, 30, and 40%). Soil containing 53% gypsum was collected from a depth of 0.5–1.0 meters below the natural ground surface, in collaboration with Tikrit University. To evaluate the mechanical properties of the soil, an unconfined compression (UCS) test was conducted on both natural samples and samples treated with various additives. The results showed that dual treatment using additives with fine particles represents an effective solution for improving the compressive strength of gypsum soils. It was found that an optimal ratio of fine particles achieves the highest strength value. Gypsum soil treated with nano-silica fume with 10% fine particles recorded the highest improvement in unconfined compressive strength, reaching approximately 93%. Soil treated with silica fume with 20% fine particles achieved an improvement of approximately 82%, while the improvement reached approximately 73% when using fly ash with 20% fine particles.

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1. INTRODUCTION

Collapsible soil is defined as soil that undergoes significant volume changes upon exposure to moisture, resulting in radical rearrangement of its particles without any change in the applied load [1], [2]. The Gypsum is a common a mineral salt, chemically known asa hydrated calcium sulfate ($CaSO_4 \cdot 2H_2O$). Gypsy soils are relatively rigid in their dry state, but they gradually lose this rigidity upon exposure to water or soaking, leading to structural collapse and increased compressibility. This is attributed to the dissolution of calcite and silicate compounds that stabilize soil particles, weakening the bonds between them [3], [4]. To address this problem, many additives have been used to improve behavior of gypsy soils, such as the lime and bituminous a materials. In recent years,the nanomaterials have emerged as a promising new approach to soil improvement, demonstrating their ability to increase soil strength and reduce its potential for collapse. The importance of this research area is increasing becausethe many civil engineering projects are constructed in areas containing gypsum deposits. Replacing the gypsum soil with an alternative soil with good properties is a possible solution, but it is often expensive and uneconomical when the depth of the replacement layers increases. Hence, research has turned to developing more effective soil treatment techniques before starting construction work [5]. Soil stabilization is known as one of the important means, of improving the engineering properties of soil by increasing its resistance and durability, by reducing the limits of compression, theshrinkage,a swelling, and permeability using chemical and/or mechanical techniques [6]. Traditional stabilizers such as lime, cement, fly ash, rice husk ash, and corn leaf ash have been widely used in many engineering projects, and their effects have been studied in detail in references [7]-[10]. However, in recent years, nanotechnology and nanomaterials have emerged as a modern research trend that has the received increasing attention [11]-[13]. Although some studies have addressed the role of nanomaterials in soil improvement, available research remains limited, particularly regarding their impact on undesirable geotechnical soil properties. In this context, gypsum soil has received particular attention from researchers due to its high tendency to collapse and sudden loss of stiffness when exposed to water, which leads to a significant increase in compressibility. The goal of improving this type of soil is to reshape its structure and enhance its stability using different techniques and materials depending on the nature of the structures and the defects to be addressed.

Gypsum soil improvement methods can be divided into two main types:

1. Physical improvement: This relies on mechanical methods to improve soil properties, such as compaction, stone columns, pre-wetting treatment, dynamic compaction, and others [14].

2. Chemical improvement: This relies on adding chemical materials to improve the soil and enhance its resistance, such as dried calcium chloride, lime, cement, bentonite, and bituminous materials such as cut asphalt [15], [16].

1.1. Micro- and nanomaterials

Over the past fifteen years, and particularly in the last decade, micro- and nanomaterials have witnessed remarkable development as an interdisciplinary field combining chemistry, physics, biology, and engineering [17]. Among these materials, silica fume (SF) is a prominent byproduct of silicon and ferrosilicon manufacturing processes. Silica fume is produced by reducing pure the quartz to silicon at temperatures up to 2000 °, where silicon dioxide oxidizes and shrinks to form amorphous microparticles, also known as microsilica or volatile silica [18]. Several studies have been conducted to evaluate the effect of nanomaterials on soil properties. For example, Gallagher et al. [25] and Chobasti and Kotanai [26] used nanomaterials in sandy soil, while Majeed and Taha [22] conducted experiments mixing several nanomaterials, such as nanocrystalline copper oxide, nanomagnesium oxide, and nanoclay, to study their effect on soft soil. For his part, Al-Azzawi et al. [19] investigated the behavior of silty clay soil when mixed with silica fume at concentrations of 5, 10, and 15%. The results showed a significant improvement in swelling pressure and compressive strength. Iranpour and Haddad [27], as well as Bharathan et al. [20], also indicated that the use of various types of nanomaterials—such as nanoclay, nanoalumina, nanocopper, and nanosilica—contributed to a reduction in permeability with increasing silica fume content. Experiments showed that the unconfined compressive strength (UCS) increased with increasing SF content up to 15%, before beginning to decline. In the same context, Taha and Taha [23] conducted a laboratory study on four types of clayey soil mixed with three types of nanomaterials (nano-clay, nano-alumina, and nano-copper) in different proportions. Verma and Maheshwari [24] focused on adding nano-titanium dioxide at ratios ranging from 0–1% by weight to clayey soil, and the results showed that the optimal ratios clearly reduced the likelihood of collapse. On the other hand, Albasuda and Khadir [28] studied the effect of fly ash and silica fume as ultrafine aggregates on gypsum soil. The results indicated that adding (2)% fly ash and (4)% SF reduced the collapse tendency by more than 83% at these optimal ratios. Although many previous studies have focused on improving the behavior of gypsum soil using lime or traditional cementitious materials, most have addressed only one material or focused on general properties such as shear strength or collapse tendency. In contrast, the unconfined compressive strength (UCS) of gypsum soils treated with lime, silica fume, or nanosilica remains insufficiently studied when using precise and graded proportions of these materials. Hence, this study aims to fill this gap by separately evaluating the effect of these additives on improving the unconfined compressive strength of gypsum soils.

2. Experimental Program

2.1. Gypsum Soil

This study used a soil sample containing 53% gypsum. This sample was the obtained from a depth of 0.5 to 1 meter, below the natural ground surface and was donated by Tikrit University Figure 1. The sample was then transported to theSoil Mechanics Laboratory in the Civil Engineering Department at the the Tikrit University. aresults of a physical and chemical tests of the gypsum soil are shown in the Table 1.

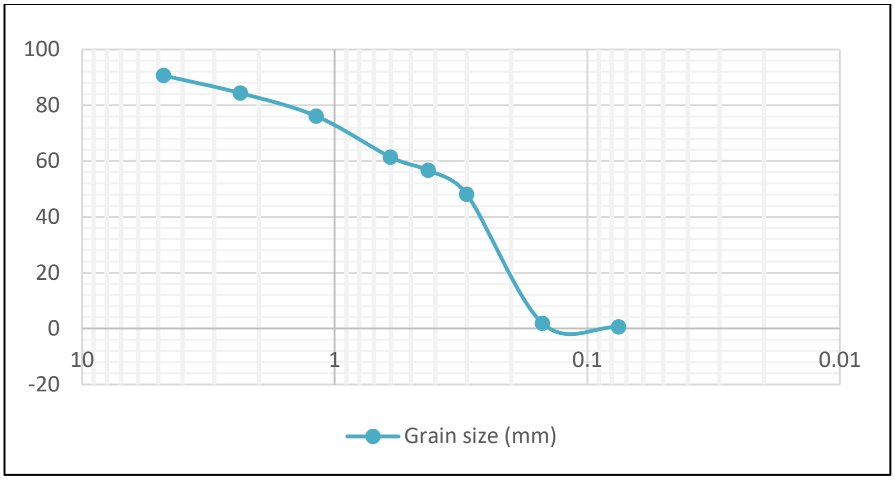

Figure 1. Gypsum soil grain size distribution.

2.2. Clay Soil

clay soil used in this study was purchased from University Kirkuk. fine particles that make up clay soil are less than 0.075 mm in diameter. Clay soil contains 95% clay and is characterized by large intergranular spaces, which helps it retain water for long periods and increase its moisture content. Because clay soil is easily compressible and contains very fine, solid particles, it is difficult to break down later Figure 2. Table 2 presents the results of the physical and the chemical properties of clay soil.

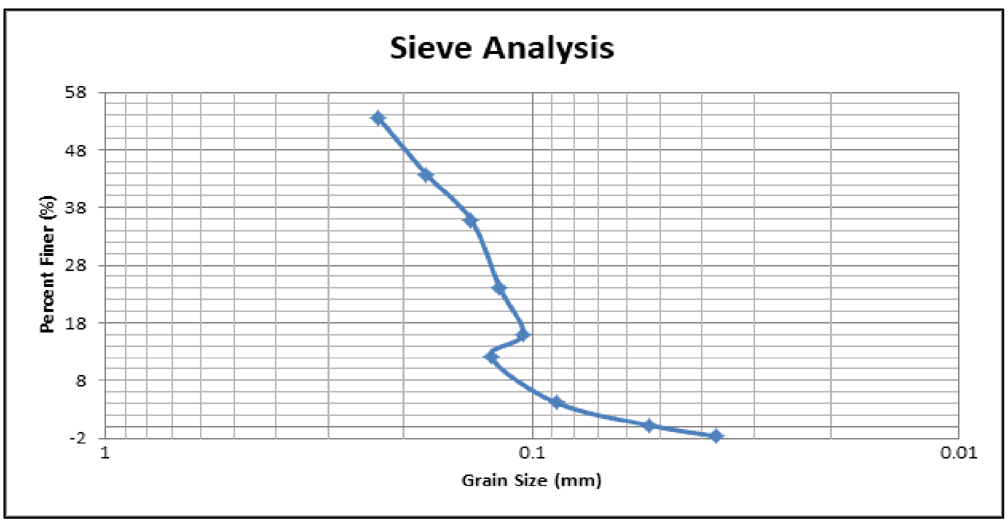

Figure 2. Grain size distribution of clay soil.

Table 1. Physical properties of the, gypseous soils.

Index property	The Value	The Specification
A Specific Gravity Gs	2.41	ASTM D-854
Natural Water Content (%)	5.71	ASTM D-2216
D10 (mm)	0.11	
D30 (mm)	0.22	
D60 (mm)	0.43	
Liquid Limit (L.L)	N.L	ASTM D-4318
Plastic Limit (P.L)	N.P	ASTM D-4318

Coefficient of uniformity Cu	3.125	ASTM D-4254
Coefficient of uniformity Cc	1.125	ASTM D-4254
Maximum dry unit weight (kN/m3)	19.10	ASTM D-694
Field dry unit weight (kN/m3)	15.9	ASTM D-1556
Classification according to USCS	SP	ASTM D-2487
Friction angle, ϕ in (º)	37.3	ASTM D-3080
Cohesion c in (kpa)	5.8	ASTM D-3080
Gypsum content %	53.16%	Al-Mufty and Nashat [20]

Table 2. Physical properties of clayey soils.

The Index property	The Value	Specification
The Specific Gravity Gs	2.81	ASTM D-854
Maximum dry unit weight (kN/m3)	17.5	ASTM D-694
Friction angle, ϕ in (º)	10.2	ASTM D-3080
Cohesion c in (kpa)	26	ASTM D-3080
Liquid Limit (L.L)	42	ASTM D-4318
Plastic Limit (P.L)	22	ASTM D-4318
Optimum moisture content	15	ASTM D-2216
Coefficient of uniformity Cu	2.32	ASTM D-4254
Coefficient of uniformity Cc	0.30	ASTM D-4254

2.3. Silica Fume

The The standard parameters include the basic physical and chemical properties of silica dust. Silica dust particles are very small, with more than 95% of them being less than one millimeter in size. The addition ratio of this material was 4% [21] . the Table 3 shows properties of the silica dust in this research.

Table 3. The Chemical composition of silica fume.

Content	Percent (%)
Sic	0.04
SiO_2	85-97
Al_2O_3	1.30
MgO	0.90
Na_2O	0.29
P_2O_5	0.13
SO_3	0.11
Cl	0.02
CaO	0.44
K_2O	1.02
C	0.33
Fe_2O_3	0.80

2.4. Nano-Silica

The Hydrophobic silica fume with a different specific surface area produced in China at 2% by weight of dry soil was used [22] . Table 4 shows the properties of the nano silica fume used during this study.

Table 4. the Chemical and physical properties the nano-silica.

Properties	Nano silica (waterproofed)
Appearance	White
Silicon Oxide Content	98.1%
Particle Size distribution (D 50)	20 nm
The Specific Surface Area	134 m2 /g
The Density	0.04 g/cm3
Moisture	2.7 %
Loss on ignition	5.2 %
Surface treatment	Hydrophobic
PH	5.5 – 6

2.5. Fly Ash

Fly ash is a pulverized material resulting from coal combustion in power plants. It is mainly composed of silica, alumina, and iron oxide. Fly ash is used in concrete to strengthen and increase its durability, as well as to reduce water permeability. Fly ash is primarily composed of oxides of silicon, aluminum, iron, and calcium. The utilization rate of fly ash was 8% [18] .Table 5 shows the chemical composition of fly ash. It also shows the properties of the fly ash used in this study.

Table 5. Chemical composition of fly ash.

Chemical compound	Percentage
K_2O	1.296
Al_2O_3	18.273
CaO	3.145
LiO	14.87
Na2O	0.683
MgO	1.191
TiO_2	0.949
MnO	0.055
Fe_2O_3	7.288
P_2O_5	0.199
SiO_2	51.999
Sum	99.948

2.6. Unconfined compression (UC) Test

primary purpose of this test is to determinet unconfined compressive strength, which is then used to calculate undrained, cohesionless shear strength clay under undrained conditions. According to the ASTM standard, unconfined compressive strength (qu) is defined as compressive stress at which an unconfined cylindrical soil specimen fails in a simple compression test. Additionally, in this test method, the unconfined compressive strength is taken as the maximum load achieved per unit area, the load per unit area at 15% axial stress, whichever occurs first during the test procedure. In the unconfined compression test, the cylindrical soil specimen is loaded axially (compressive axial stress, σ1) without lateral support, which means that the secondary principal stresses σ2 and σ3 (confining stress) are zero, as shown in Figure3.

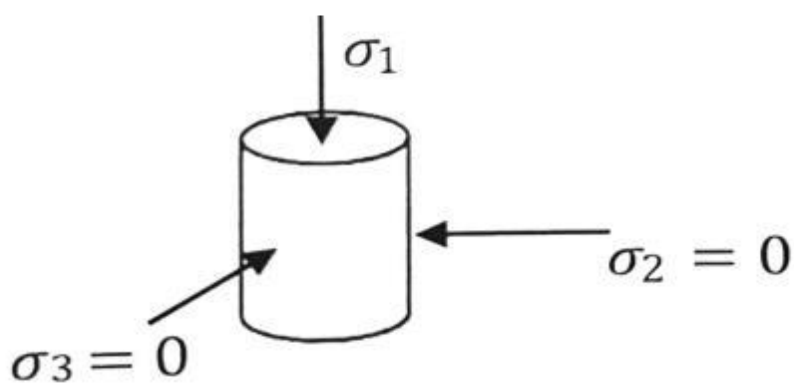

Figure 3. The cylindrical element subjected to only σ1 axial compression.

Mohr circle can be drawn for stress condition at failure , the minor principal stress is zero , Mohr circle passes through the origin as shown in Figure 4 . The failure envelope is horizontal (Φ = 0) . The cohesion intercept is equal to radius of the circle as presented in Eq. 1.

$$Su = Cu = \sigma\_1/\sigma\_2 = q\_u/2 \quad (1)$$

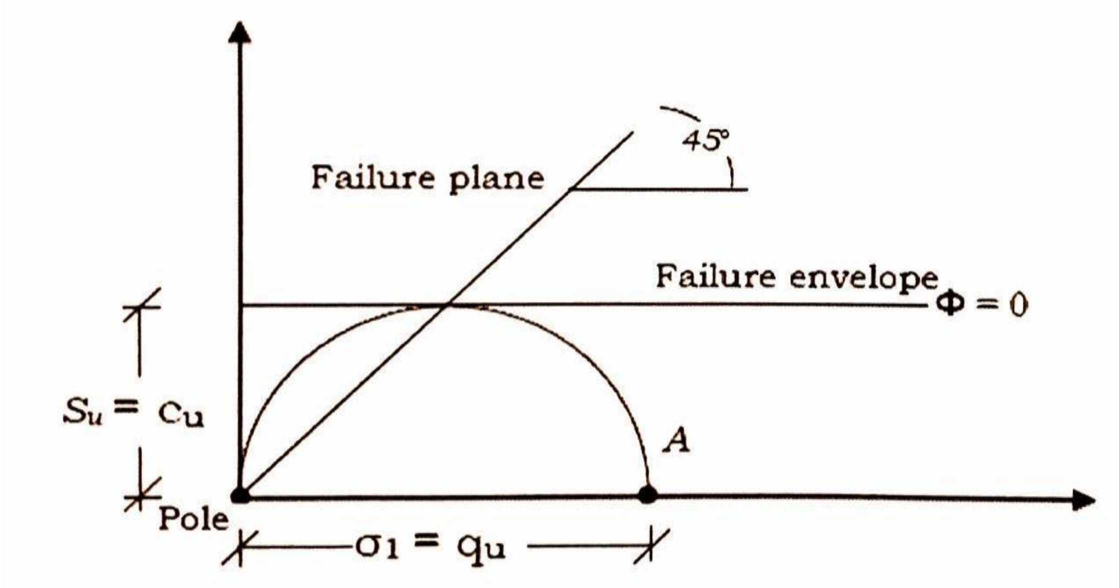

Figure 4. Mohr circle of unconfined compression test in terms of the total stress.

2.7. Samples Preparation

The experimental samples were prepared from gypseous soil and stabilized with various additives. The treatment involved incorporating clay soil at proportions of 0%, 10%, 20%, 30%, and 40%, in addition to fixed contents of silica fume (4%), nano-silica (2%), and fly ash (8%). All samples compacted under soil field unit weight with an initial saturation level of 50% to achieve the best soil interaction [19]-[21]. The samples are coated with a double layer of nylon and aluminum and left to cure for a period of seven days. After curing time the sample is removed from the cylinder using a designated pressure column, and the surface is leveled using a dedicated cutting tool. After removing sample, its dimensions (height, diameter, etc.) are measured.

The sample is weighed to determine its density by determining its volume and weight. The sample is placed in a free-pressure device so that its vertical axis is as perpendicular to the load disc as possible. We begin applying the load and take the meter readings regularly, continuing until the sample collapses and the sliding surface becomes clear. Figure 5 illustrates the model in the device.

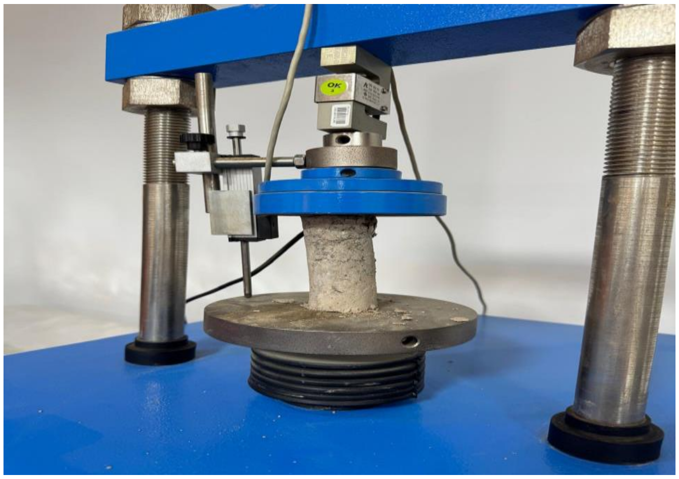

Figure 5. The model examined by the unconfined compression device.

3. RESULTS AND DISCUSSION

In Dust samples treated with 2% nano silica, 4% silica fume, and 8% fly ash, as well as fine dust particles at 0, 10, 20, 30, and 40% concentrations, were evaluated for unconfined compression.

Figure 6 show the results of the unconfined compression test of gypseous soil treated with fine materials at ratios from 0 to 40% with addition of silica fume at a rate of 4%. main results showed a clear differences in compressive strength and strain behavior with varying clay content, as follows:

At 0% of fine content A nearly linear curve then gradual failure without a sharp peak, peak ≈ 105–115 kPa at ~10–11% strain. Ultrafine silica fumarate (SF) fills microvoids and activates pozzolanic reactions with available calcium from the gypsum, forming a C–S–H gel that increases cohesion. However, the absence of clay means a lack of active surfactants/alumina and complementary silica, so the structure remains relatively "brittle."

At 10% of fines content, the strength was relatively low (approximately 105 kPa) due to the clay content not being sufficient to fill most of the voids between the gypsum soil particles. Although silica improved cohesion through its pozzolanic interactions, the structure remained relatively porous.

At 20% of fines content, the highest compressive strength was recorded (approximately 200 kPa) with a greater strain tolerance before failure. This is because the clay content in this case was optimal for void filling and distributing the pozzolanic reaction products (C–S–H) resulting from the silica content, resulting in a cohesive and strong mixture. The unconfined compression test increased by about 82% than at 0% fine particle content.

At 30% of fines content, the strength decreased slightly (approximately 150 kPa) compared to 20%, despite improving over 10%. The likely reason is the increased clay mineral content, which increased plasticity and reduced intergranular friction, resulting in a lower ultimate strength.

At 40% of fines content, the strength was the lowest among all samples (approximately 95 kPa). This was due to the extremely high plasticity and increased pore pressure at high moisture content, which weakened the mechanical structure despite the presence of silica.

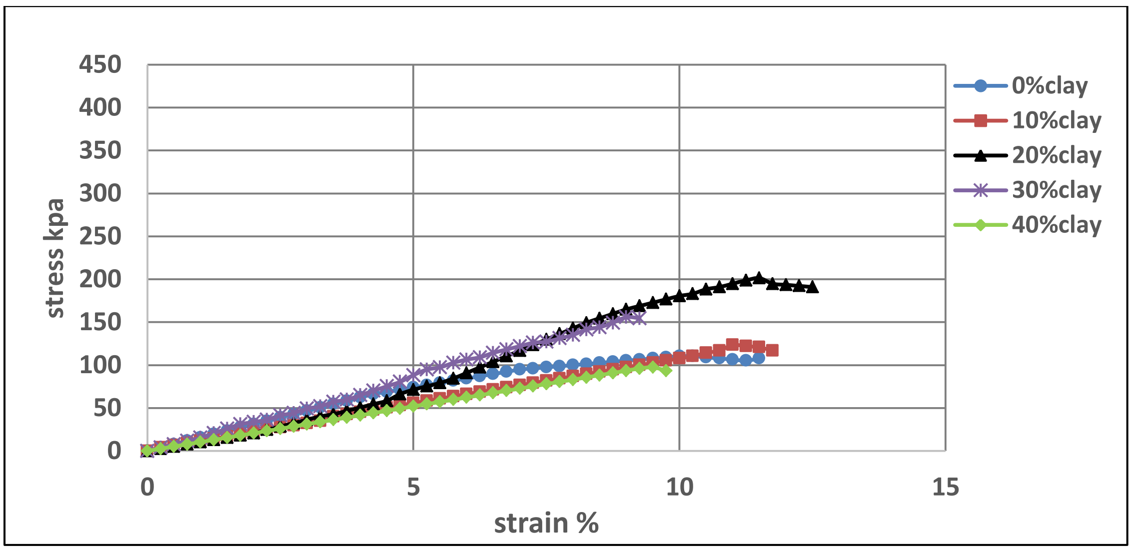

Figure 6. Stress-strain correlation of gypseous soil treated with the silica fume, and fine soil particles.

Figure 7 show the results of the unconfined compression test of gypseous soil treated with fine materials at ratios from 0 to 40% with addition of nano-silica fume at a rate of 2%. main results showed a clear difference in compressive strength and strain behavior with varying clay content, as follows:

At 0% of fines content, the strength was the lowest (approximately 110 kPa) due to the porous nature of the gypsum soil and the lack of sufficient fine materials to fill the voids. Nano silica partially improved cohesion through] formation of hydrated calcium silicate (C–S–H) complexes, but absence of clay limited the significant increase in strength.

At 10% of fines content, it could be observed significant improved in strength (exceeding 385 kPa), the highest performance among all samples. This is because this ratio provided sufficient fine particles to fill voids and achieve a homogeneous distribution of the pozzolanic products resulting from the nano silica reaction, forming a cohesive and rigid earth matrix. The unconfined compression test increased by about 93% than at 0% fine particle content.

At 20% of fines content, the strength decreased to approximately 170 kPa, possibly due to increased plasticity and reduced internal friction, despite the continued benefit of the nano silica effect. Increasing the clay content also limited the optimum dry density, affecting the ultimate strength.

At 30% of fines content, the strength was recorded at approximately 150 kPa, which is lower than the strength at clay content of 20%. This behavior is due to a significant increase in plasticity and high pour water pressure under load, leading to faster structural failure.

At 40% of fines content, the strength was among the lowest (approximately 140 kPa), due to the significant clay predominance, which led to ductile behavior and weak structural bonding. Failure is accelerated due to reduced internal friction and increased deformation.

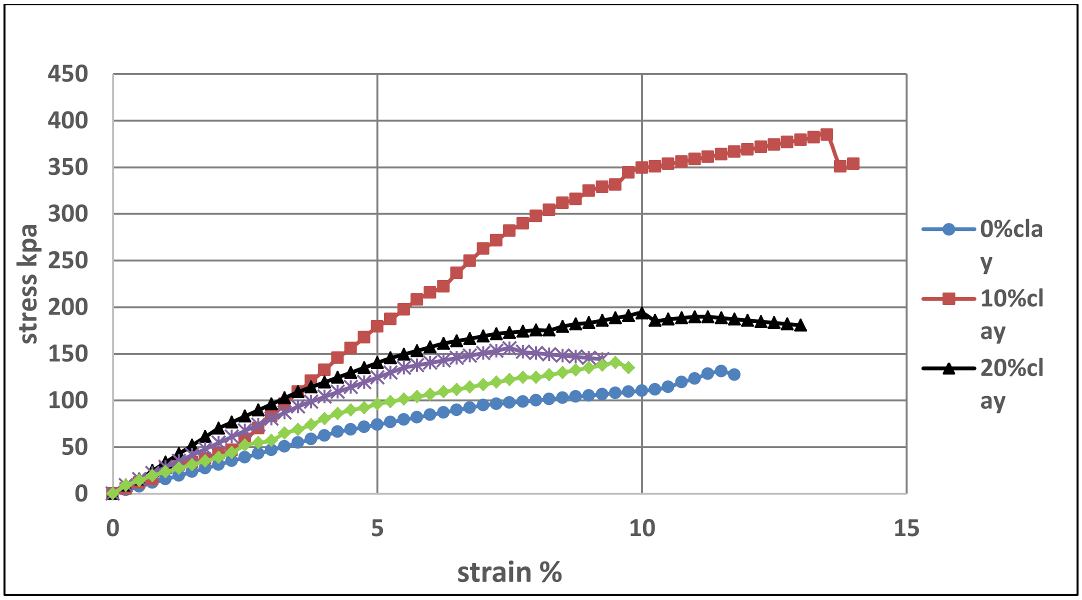

Figure 7. Stress-strain correlation of gypseous soil treated with nano-silica, and fine soil particles.

Figure 8 show the results of the unconfined compression test of gypseous soil treated with fine materials at ratios from 0 to 40% with the addition of the fly ash at a rate of 8%. The main results showed a clear difference in compressive strength and strain behavior with varying clay content, as follows:

At 0% of fines content, the gypsum soil with 8% fly ash remained characterized by pronounced voids and weak intergranular bonding, resulting in the lowest strength value.

At 10% fines content, a significant improvement occurred due to void filling and improved grain gradation, leading to a clear increase in strength.

At 20% fines content, the best performance was achieved, as voids were filled evenly and degree of cohesion increased with activation of the fly ash pozzolanic reaction. This resulted in highest unconfined compressive strength value, unconfined compression test increased by about 72% than at 0% fine particle content.

At 30%, strength began to decline relatively due to the increased proportion of fines content, which increased the soil's plasticity and increased water demand, weakening the structure despite the improved plasticity.

Finally, at 40%, fines content became dominant, resulting in increased microporosity and weak intergranular bonding, reflected in a clear decrease in strength and a more brittle behavior.

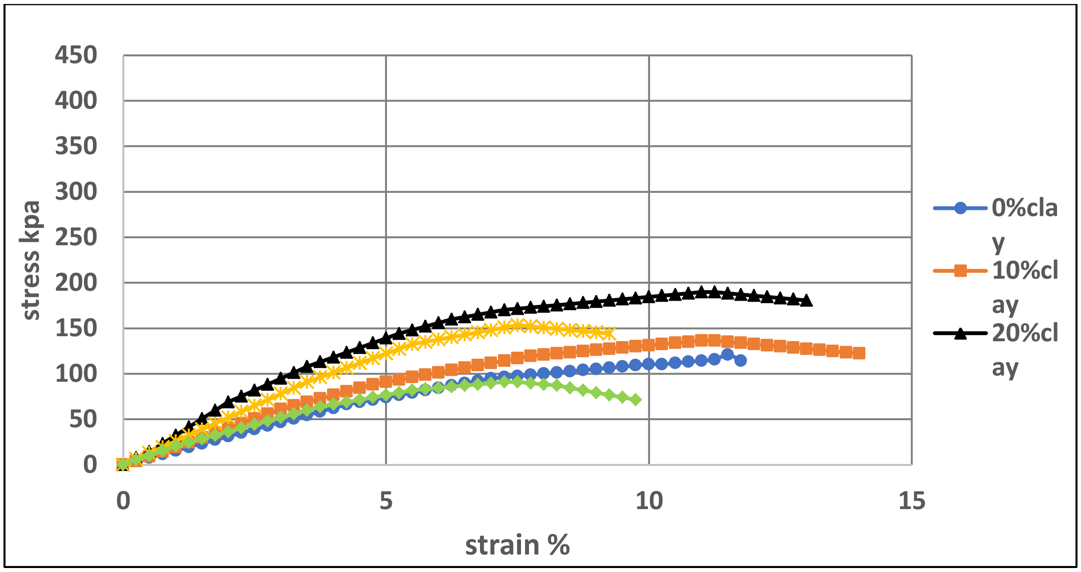

Figure 8. Stress-strain correlation of gypseous soil treated with the nano-silica and fine soil particles.

Figure 9 shows the variation of the unconfined enhancement ratio (UER (%) which was determined as in Eq. 2, with treated gypsous soil and fine particles for the three types of additive. It could be observed that nano-silica fume-treated soil with fine particles achieved maximum unconfined enhancement ratio (UER (%).

$$UER\ (\%) = \ (UC\ treated - UC\ untreated)/(UC\ untreated) * 100\% \tag{2}$$

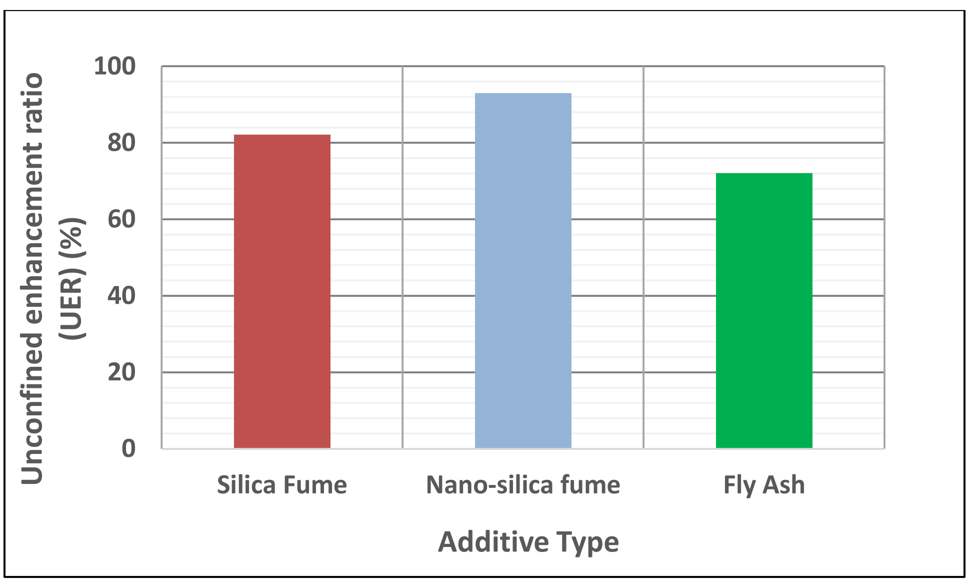

Figure 9. Variation of unconfined enhancement ratio (UCR) with additive type.

The results showed that the effect of fine materials depends on the type of additive. In the case of fly ash-treated soil, the highest UCS was achieved at approximately 20% fine particles, then the strength decreased at 30–40% due to increased plasticity and a weakened grain structure. The behavior of silica fume-treated soil was similar, with a peak near 20% fine aggregate due to void filling and pozzolanic interaction, followed by a decline at higher ratios. In contrast, nano-silica-treated soil showed a clear superiority at 10% fine particles, likely due to its high surface area and its role as nuclei for precipitation of hydration products. Further increases led to agglomeration, higher water demand, and consequently a lower UCS. Therefore, a fine particle ratio of approximately 10% with nano-silica and 20% with silica fume or fly ash is recommended for achieving the best unconfined compressive strength for gypseous soils.

4. CONCLUSION

The main conclusions of the present study could be summarized as follows:

1. The results show that incorporating 2% nano-silica into gypseous soil significantly improves unconfined compressive strength. However, this improvement is highly dependent on the percentage of fine particles added. The optimal percentage of fine particles was 10%, where the highest strength was achieved. Higher percentages of fine particles (20% or more) resulted in decreased strength due to increased plasticity, reduced internal friction, and increased pore pressure.
2. For silica fume and fly ash-treated soil with fine particles, there is an ideal proportion of fine particles of 20% that achieves the optimal balance between the mechanical filling effect and the increase in chemical cohesion, while higher proportions of clay lead to increased plasticity and reduced resistance.
3. Nano-silica fume-treated gypseous soil with 10% of fine particles achieved approximately 93% unconfined enhancement ratio, while silica fume and fly ash-treated gypseous soil with 20% of fine particles achieved approximately 82 and 73% unconfined enhancement ratio respectively.
4. It can be said that the dual treatment (additive materials and fine particles) at a suitable moisture content provides an effective solution to improve compressive strength of gypseous soil, with optimum fine particles ratio achieving maximum strength before the mechanical properties are negatively affected due to increased plasticity.
5. Future research is recommended to investigate different proportions and combinations of silica fume, nano-silica, and fly ash, as well as to examine the effects of moisture content and curing period. Long-term durability under environmental conditions such as wetting–drying and freeze–thaw cycles should also be evaluated..

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