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Collapsible Gypseous Soil Stabilization by Calcium Carbide Residue and Sulfonic Acid

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Abstract: Gypseous soil is a collapsing soil that has not yet been approved as a construction material since its behavior under water, temperature, and pressure is unreliable and unpredictable. Researchers and scientists are always searching for new and creative ways to optimize the benefits of calcium carbide residue (CCR) recycling, which is a byproduct of the acetylene industry and includes a substantial quantity of $Ca(OH)_2$. Therefore, it is a suitable choice for utilization as a chemical stabilizer to improve the engineering features of problematic soils. However, this study explores the potential for enhancing the engineering characteristics of gypseous soil by utilizing (CCR) combined with linear alkyl benzene sulfonic acid (LABSA) to form a geopolymer. The soils utilized in this work are gypseous collapsible soils. Standard tests were conducted on these soils to identify the physical and mechanical characteristics. The geopolymer preparation was accomplished by merging a dilution of LABSA with a geopolymer (solid to liquid), blending the proportions. Three different types of disturbed natural granular-gypseous collapsible soils with different properties and various gypsum contents with percentages of 20%, 35%, and 50% were used. Mixtures of soils containing (2.5%, 5%, and 7.5%) of the geopolymer mix content were made. The single oedometer test (SOT) and the double oedometer test (DOT) were carried out to ascertain the lowest collapse potential value correlated with the ideal geopolymer mixing ratio. The adequate geopolymer percentage was found to be 5% since it resulted in the maximum reduction in collapse potential compared to the natural soil. The direct shear test is employed to ascertain the soil samples' cohesiveness and friction angle. The results show a slight reduction in the angle of internal friction and increased cohesion (c). For stabilizing gypseous soil in engineering projects, a combination of LABSA and CCR can be utilized as a workable, sustainable, and environmentally friendly substitute.

Keywords: gypseous soil; collapsible soil; geopolymer-stabilized; calcium carbide; sulfonic acid; shear strength; direct shear test

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1. Introduction

Gypsum-rich soils are created by geoclimatic environmental conditions and are found in arid regions of the world where there is not enough annual precipitation to leach the gypsum from the soils. About 1.5 million km^2 or so of the world's total surface is covered with gypseous soils, according to the United Nations Food and Agriculture Organization [1,2]. Iraq is among the countries with gypseous soil, making up 30% of its entire territory and found in many places [3]. Gypseous soil (soil containing adequate quantities of gypsum) is a collapsing soil that has not yet been approved as a construction material since its behavior under water, temperature, and pressure is unreliable and unpredictable [4]. Gypsum is a highly soluble salt that is widely recognized for its ability to dissolve easily. Consequently, the presence of gypsum in soil has a harmful impact on subgrade soils, buildings, and earth structures. Water content variations in gypseous soil cause the gypsum, which serves as a cementing agent, to dissolve within the soil mass. This can lead to one or more of three processes: the first is the breakdown of the bonds holding soil particles together, which is followed almost immediately by the collapse of the soil structure. Consolidation is the second process, and leaching, which happens while water keeps flowing through the soil mass, is the third. When loading is applied, the combination of these processes will cause the earth to settle significantly [5]. Gypseous soil is regarded as weak soil in the presence of water. Its bearing capacity is often low, and its strength is low. Because of this, using it as a building material carries several dangers. Researchers have shared numerous studies to enhance the engineering features of gypseous soils and to identify an inexpensive and efficient material for improving gypseous soils.

The enhancement of gypseous soils involves restructuring these soils to mitigate abrupt reductions in strength and excessive compressibility caused by water infiltration. The approach to enhancement varies based on the nature of the structures and the specific problem detected. By adopting this approach, it is possible to accomplish two different kinds of enhancement: physical and chemical. The physical aspect involves enhancing soil properties through the use of mechanical techniques such as compaction, stone columns, pre-wetting, dynamic compaction, and others [6]. Chemical enhancement techniques involve improving soil properties by adding various chemicals, such as chloride, dehydrated calcium, lime, cement, bentonite, and cutback asphalt. For example, Ref. [7] examined the stability of lime when treating gypseous soil. Bituminous materials are thought to be the primary water-proofing agents that can be applied to gypseous soil; Ref. [8] suggested cut-back bitumen, whereas Ref. [9] recommended using emulsion asphalt as a remedy. Dynamic compaction was utilized to decrease the collapse potential [10]. Ref. [11] proposed a method of treating the collapsibility of gypseous soils by grouting. Ref. [12] utilized recycled fine asphalt pavement, recycled coarse asphalt pavement (RR), and rice husk ash (RHA) as additives and researched the impact of adding silicone to gypseous soil. Abbas and Al-Luhaibi [13] utilized a range of 2–12% of melting furnaces in their study. The findings indicated a significant reduction of around 91% in collapsibility. Environmentally-friendly and cost-effective soil stabilizers have been used widely to address the challenges related to problematic soils [14,15]. Ref. [16] used biopolymer material as an eco-friendly technique to improve the mechanical features of gypseous soil. Ref. [17] studied the impact of nanomaterials on stabilizing and improving gypseous soil. They also investigated the effect of magnesium oxide on collapse potential when it was mixed with collapsible gypseous soil and carbonated. Conventional stabilizers, such as lime and cement, have a notable environmental impact due to their substantial emissions of greenhouse gases (GHGs), high energy consumption during manufacture (mostly carbon dioxide, CO_2), and the release of particulate matter into the air throughout the manufacturing process. Cement manufacture is a prominent contributor to greenhouse gas (GHG) emissions due to its high energy requirements, resulting in the generation of one metric ton of carbon dioxide (CO_2) for every ton of cement produced [18].

The term 'geopolymer' was initially coined by Davidovits in the 1970s, and was later utilized to a class of solid materials synthesised through the reaction of silica- and alumina-rich materials with an alkaline solution.

Due to the energy efficiency, environmentally friendly nature of the process, and excellent engineering properties, geopolymer binders are fast emerging as materials of choice for highly demanding civil engineering applications. However, limited research has been conducted on particular applications in soil stabilization. Few published papers on the subject exist [18,19].

Researchers and scientists are always searching for new and creative ways to optimize the benefits of CCR recycling. Studies focus on CCR-stabilized soil, although strength development is the main focus. Expanding one's understanding to include other engineering properties is beneficial. Ref. [20] investigated the utilization of a blend of CCR and FA (fly ash) as a sub-base material for roads. The results demonstrated that CCR offered the advantage of being cost-effective, while also providing optimal rigidity. Ref. [21] demonstrated a substantial improvement in the engineering characteristics of lateritic soil that was stabilized with CCR as the curing period progressed. This confirms the occurrence of an interaction between the calcium hydroxide present in CCR and the pozzolanic material found in the clay component of lateritic soil. Ref. [22] found that a mixture of CCR and fly ash (FA) can be utilized to enhance the performance of traditional Portland cement for soil stabilization. Optimal proportions of CCR, FA, and clay result in the attainment of superior strength and durability. CCR and PPF (polypropylene fiber) are applied to black cotton soil in various proportions to improve its geotechnical properties and increase soil strength [23].

Al-Safi et al. [24] focused on effects of intrinsic sulfate in gypseous soil on its collapsibility potential when stabilized with fly ash geopolymer binder. The results showed the formation of geopolymer gel with higher strength and more sulfate resistance than Portland cement paste in binder.

The aim of the current work is to study and evaluate the influence of the geopolymer additive on the engineering features of gypseous soil. This investigation targets the parameters of collapse potential and shear strength. The objective of the current study is to use a treatment material that utilizes sulfonic acid and calcium carbide residue geopolymer to solve the collapse potential problems of gypseous soil. Various percentages of geopolymer were added to three types of gypseous soil.

2. Materials

2.1. Soil

The soils utilized in this work are three different types of disturbed natural granular-gypseous collapsible soil selected arbitrarily and then collected from three different sites. The first one, brought from a site located in Karbala Governorate southwest of Baghdad in Iraq, was designated as soil 20, with a gypsum content of 20%. The other two soils were brought from sites located in Tikrit city in Salah Al-Dean Governorate north of Baghdad in Iraq. They were designated as soil 35 with medium gypsum content (35%), and soil 50 with a high gypsum content of 50%. During that season, the samples were above groundwater from a depth between 1 and 1.5 m under the natural ground surface. After removing the top layer of sand, manual tools were employed to collect the disturbed samples.

The soils under examination were subjected to various necessary geotechnical characterization tests to identify their physical features, as reported in Table 1. The grain size distribution was made according to specification ASTM D 422 [25], the dry sieving method. The soils were classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). The grain size distribution of the soils is presented in Figure 1.

The specific gravity values of the soil solids were determined according to ASTM, D-854 [26]. Distilled water is usually used for the determination of specific gravity, but it is advisable to use kerosene rather than distilled water when the soil specimens contain a significant fraction of gypseous material or organic matter. So, kerosene was used to avoid the dissolution of gypsum.

The liquid and plastic limit (Atterberg limits) tests were performed on the soil passed from the sieve (No. 40), and for drying, the temperature was kept constant at 45 to 50 °C due to the substantial amount of gypsum in the soil (ASTM 2216-80) [27]. The liquid limit was performed according to (BS 1377, 1976, test No. 2) [26]. The plastic limit test was performed following the procedure of (ASTM D4318, 2017) [28].

The gypsum content was established by the method proposed by Al-Mufty and Nashat [29]. According to this method, the soils were oven-dried at 45 °C until the specimen weight was constant. The sample was then dried at 110 °C so as to ensure that the weight remained constant. The calculation for gypseous contents can be done consistently with the following equation:

$$\chi = \left[\frac{W_{45^\circ c} - W_{110^\circ c}}{W_{45^\circ c}}\right] \times 4.778 \times 100 \quad (1)$$

where:

χ = gypseous contents (%),

$W_{110^\circ C}$ = the specimen weight by 110 °C,

$W_{45^\circ C}$ = the specimen weight by 45 °C,

4.778 = inversing rate of molecular weight of hydrating water to molecular weight of gypsum.

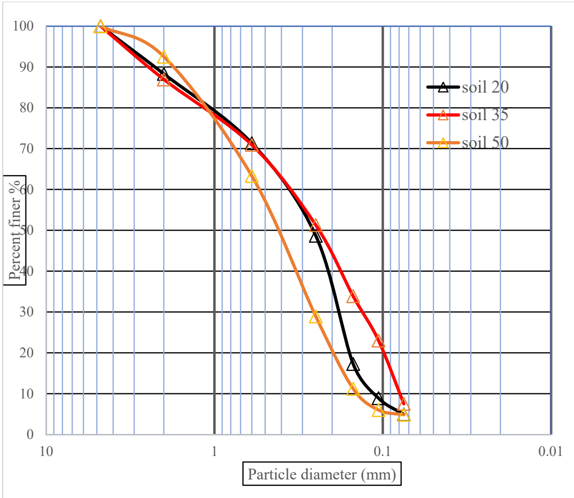

Figure 1. The grain size distribution curves of the soils.

The Proctor compaction test was conducted to determine the soil's maximum dry density (MDD) and optimal moisture content (OMC) according to (ASTM D698) [30].

Table 1. Physical features of the soils.

Physical Features		Value			Specification
		Soil (20)	Soil (35)	Soil (50)	
Specific gravity (Gs)		2.51	2.45	2.37	ASTM D854
Atterberg Limits	Liquid limit (%) (L.L)	22	23	32	BS 1377-2
	Plastic limit (%) (P.L)	N. P	16	21	ASTM D4318 [28]
% Gravel		0	0	0	ASTM D422-00 [25]
% Sand		95.0	92.49	95.16	ASTM D422-00
% Fines		4.92	7.51	4.84	ASTM D422-00
D_{10}		0.112	0.08	0.14	ASTM D422-00
D_{30}		0.182	0.134	0.261	ASTM D422-00
D_{60}		0.36	0.36	0.55	ASTM D422-00
Uniformity coefficient (Cu)		3.219	4.501	3.931	ASTM D422-00
Curvature coefficient (Cc)		0.823	0.626	0.885	ASTM D422-00
Optimal moisture content (O.M.C) (%)		10	12.3	15	ASTM D698 [30]
$\gamma_{dry\ max.}$ (kN/m^3)		18.36	1.73	16.8	ASTM D698 [30]
The field unit weight (γ_f) kN/m^3		15.2	14.8	14.2	ASTM D1556 [31]
Gypsum content (%)		20	35	50	[32]
Classification according the USCS		SP	SP-SC	SP	ASTM D2487 [33]

N.P. = non-plastic; SP = Poorly graded sand; SC = Sand with plastic fines.

The collapse tests were performed for the pure untreated and geopolymer-treated soils by using the oedometer device according to ASTM D5333 [34] to measure the collapse potential (CP) of the soils The samples were prepared for collapse testing at the maximum dry density (MDD) and the optimal moisture content (OMC) of the pure untreated soil by gently tamping down on the sample in the oedometer ring. Two types of collapse testing were used.

2.2. Single Oedometer Test (SOT)

The tested soil sample is gradually subjected to load at the optimum moisture content in this test till vertical stress becomes equal to 200 kPa. After that, the sample is submerged in distilled water for 24 h. A collapse is indicated by the further settlement, which is detected at 200 kPa of pressure. Equation (2) is utilized to compute the collapse potential (CP).

$$CP(\%) = \Delta\varepsilon = \frac{\Delta H_e}{H_o} = \frac{\Delta e}{1 + e_0} \times 100 \quad (2)$$

where:

$\Delta\varepsilon$: is the vertical strain,
ΔH_e: is the change in the height of the soil sample caused by soaking,
Ho: is the initial height of the soil sample,
Δe: is the change in the void ratio of the soil sample caused by soaking,
eo: is the initial void ratio.

2.3. Double Oedometer Test (DOT)

Two similar samples are utilized to perform this test. While the other sample has been submerged at the start of the test, the first one is tested at its optimum moisture content (OMC). The tests on the two samples were conducted using the same protocol as the traditional consolidation test process. Any particular pressure-related soil collapse is represented by the difference between the two curves' void ratio-pressure ($e - \log \sigma_v$).

Direct shear tests were performed on pure untreated and geopolymer-treated soils using the ASTM D3080-04 [35] specification. This test aims to determine the soil's shear strength parameters before and after treatment.

2.4. Calcium Carbide Residue (CCR)

CCR, which is a byproduct of the acetylene industry, includes a substantial quantity of $Ca(OH)_2$. Therefore, it is a suitable choice for utilization as a stabilizer. The study conducted in Ref. [36] confirmed that 74 g of calcium carbide (CaC_2) and 26 g of acetylene gas (C_2H_2) may be produced from 64 g of calcium carbide (CaC_2). In view of the current situation, Iraq is making a request for an annual supply of 500 tons of CaC_2 in order to create acetylene gas. Annually, around 600 tons of CCR are produced, and the demand continues to increase. For the purpose of this research, CCR was acquired from a local industrial source in Baghdad. The factory provided CCR in a dried powder state, which is ready to be used immediately, as depicted in Figure 2. The chemical compositions of the CCR are presented in Table 2 and Figure 3, which was obtained using EDX analysis. It is a non-destructive test that reveals the elemental composition of the tested materials. Table 3 provides the physical properties of the CCR used in this study. Based on the EDX results, the main chemical composition of the major CCR is 56.33% CaO, with 10.52% SiO_2, 8.07% Al_2O_3, and 7.12% Fe_2O_3. This suggests the existence of Pozzolanic components at around 25.71%. The high quantities of $Ca(OH)_2$ and CaO in the CCR indicate its ability to undergo reactions with pozzolanic materials, suggesting that it can function as a cementitious binder.

Figure 2. CCR powder.

Table 2. The chemical constituents of CCR.

Composition	(wt.%) CCR
Calcium (CaO)	56.33
Carbon (C)	10.66
Silica (SiO_2)	10.52
Alumina (Al_2O_3)	8.07
Ferrous (Fe_2O_3)	7.12
Magnesium (MgO)	4.20
Potassium (K_2O)	1.58
Sulfur (SO_3)	0.87
Titanium (TiO_2)	0.65

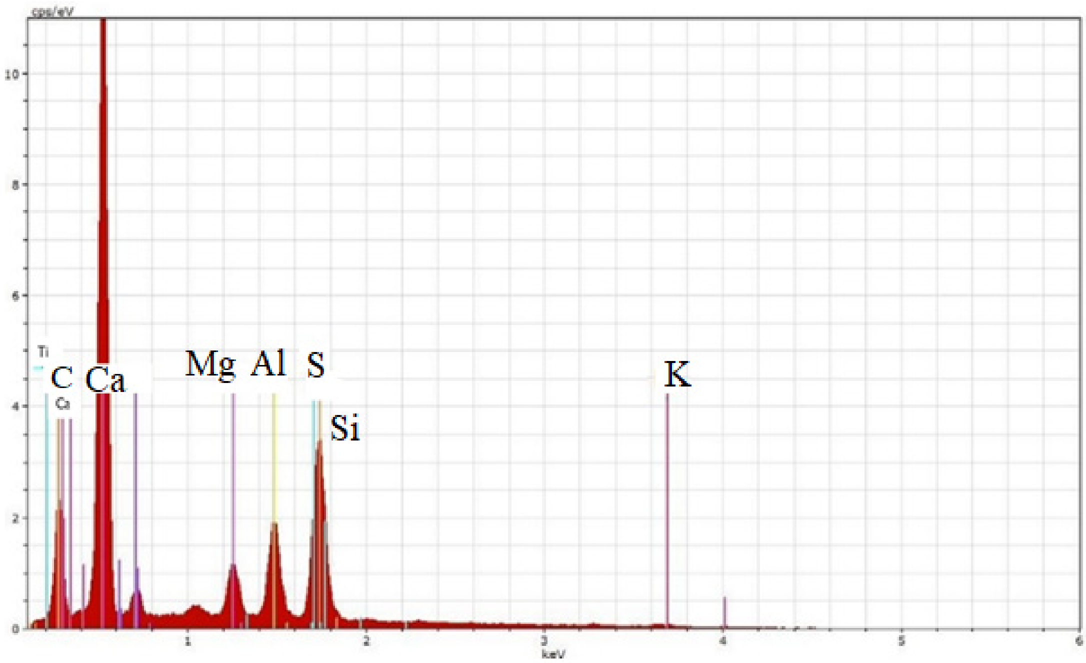

Figure 3. EDX spectrometry for the CCR.

Table 3. Physical characteristics of CCR as provided by the supplier.

Item	Property
Texture	Powder
Color	Light grey
pH (25 °C)	12.56
Specific gravity	2.223

2.5. Linear Alkyl Benzene Sulfonic Acid (LABSA)

The chemical compound sulfonic acid, also known as dodecyl benzene sulfonic acid, is referred to by its scientific name, LABSA. The primary applications of LABSA, which were utilized in this inquiry, are in the cleaning and detergent-producing industries. Table 3 lists its physical characteristics. Based on EDX analysis, the elemental analysis of LABSA is as shown in Tables 4 and 5. When LABSA is used in a laboratory, it is typically a thick liquid, as seen in Figure 4. It can be diluted straight by adding it to distilled water in order to produce a consistent and efficient alteration. LABSA was diluted with distilled water using the following percentage: 300 acid/1000 distilled water ml based on the recommendations in Ref. [37].

Table 4. The chemical constituent of LABSA.

Composition	LABSA (wt.%)
Carbon (C)	49.22
Calcium (CaO)	35.94
Oxygen (O)	10.96
Sulfur (SO_3)	1.91
Silica (SiO_2)	1.20
Magnesium (MgO)	0.46
Alumina (Al_2O_3)	0.22
Ferrous (Fe_2O_3)	0.09

Table 5. Physical characteristics of LABSA as provided by the supplier.

Item	Property
Color	Dark brown
Chemical formula	$C_6H_4SO_3H$
Texture	Liquid
Density	1.0485

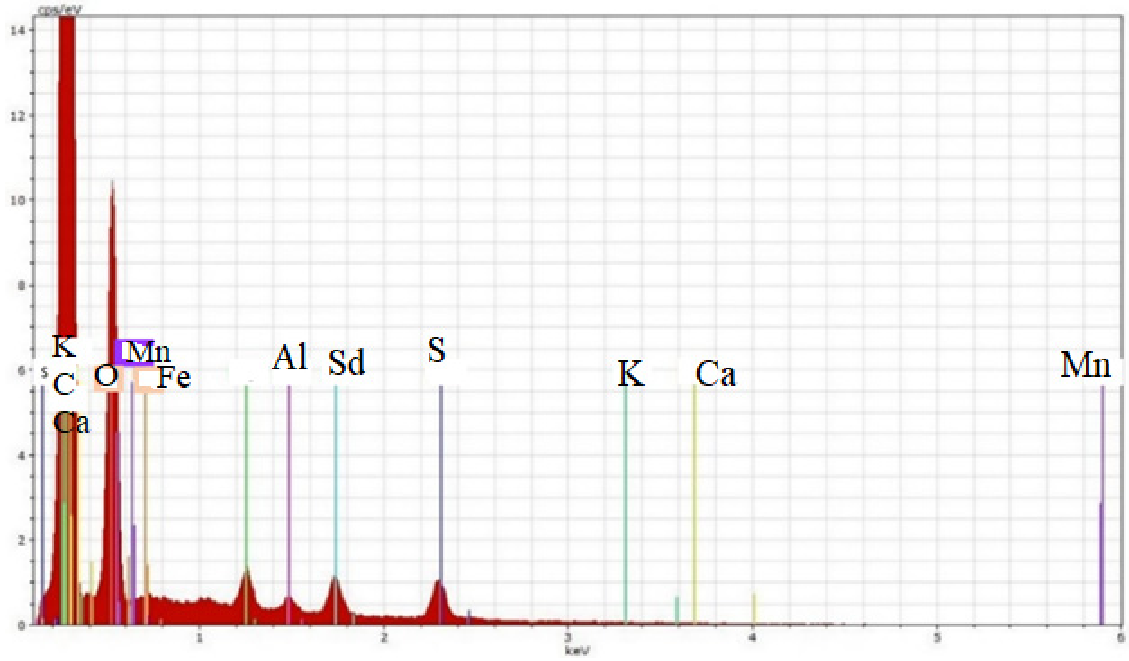

Figure 4. EDX spectrometry of LABSA.

3. Geopolymer-Treated Soil Sample Preparation

The geopolymer preparation in the present research required mixing a diluted solution of LABSA (300 mL acid/1000 mL distilled water) with a CCR blending ratio of 80% solid to 20% liquid, based on the total dry mass of the soil. This approach was based on a previous study conducted in Ref. [38]. Soil specimens were treated with geopolymer at three different percentages: 2.5%, 5%, and 7.5% of the dry mass of soil. This was done by adding the appropriate amount of CCR powder to the dry soil and blending the mixture for at least 1 min until a uniform and consistent color was achieved. Next, the geopolymer was created by combining the diluted LABSA liquid with the optimum content of water in each untreated soil. The soil and geopolymer were manually mixed for a duration of five to ten minutes to achieve a sufficiently uniform mixture. Subsequently, the prepared specimens underwent an hour-long fermentation process. Following this, the soil sample mixtures were compressed by gently tamping the sample in the oedometer ring for collapse tests and in the shear box for direct shear tests. The aim was to achieve a target dry density, which corresponds to the maximum dry density determined by the standard compaction test for each untreated soil, before conducting the tests.

4. Results and Discussion

4.1. Collapse Test Results Without Geopolymer

Figures 5–10 describe the relation between the void ratio and vertical stress, and represent the outcomes of the single-oedometer and double-oedometer tests for the three types of natural untreated gypseous soil. A 200 kPa stress level was used to calculate the collapse potential. The maximum collapsible potential observed in soil 50, which has the highest gypsum concentration, was 7.35% from SOT, so the soil is located in the moderately severe range according to ASTM D5333. The collapse potential (CP) for the same soil was determined by DOT to be 10.42%. According to ASTM D5333-03 [34], this falls within the range of soils with severe degree of collapse. The collapse potential was 6.29% and 9.67% for soil 35 from SOT and DOT, respectively, which were located in the range of soils with a moderately severe degree of collapse. For SOT for soil 20, the collapse potential (CP) is equal to 5.48%. The soil is categorized as having moderate trouble, while the collapse potential (CP) of the soil sample measured by DOT is equal to 8.52%, so the soil is classified moderately severe trouble.

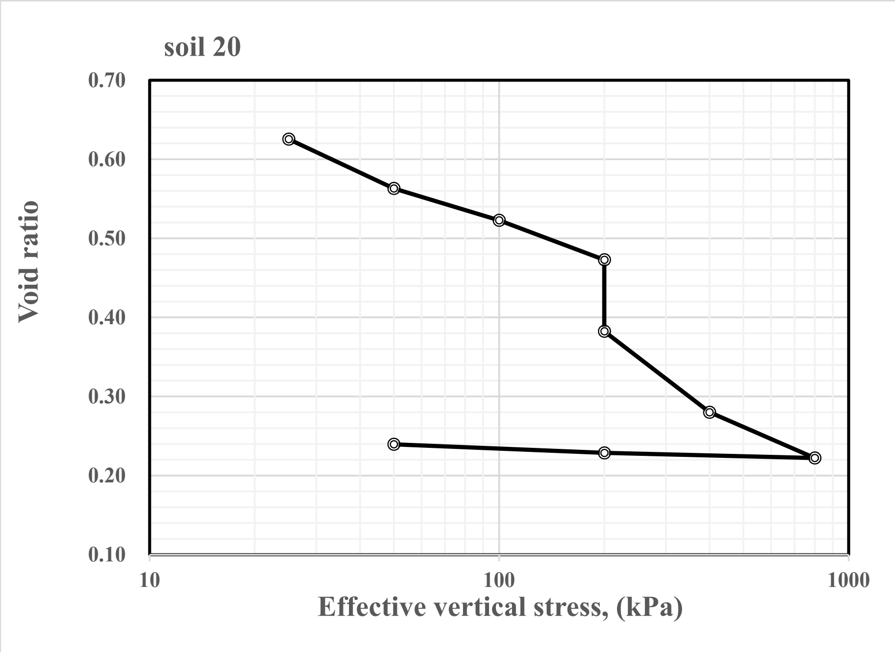

Figure 5. Single oedometer test result for the natural (untreated) gypseous soil 20.

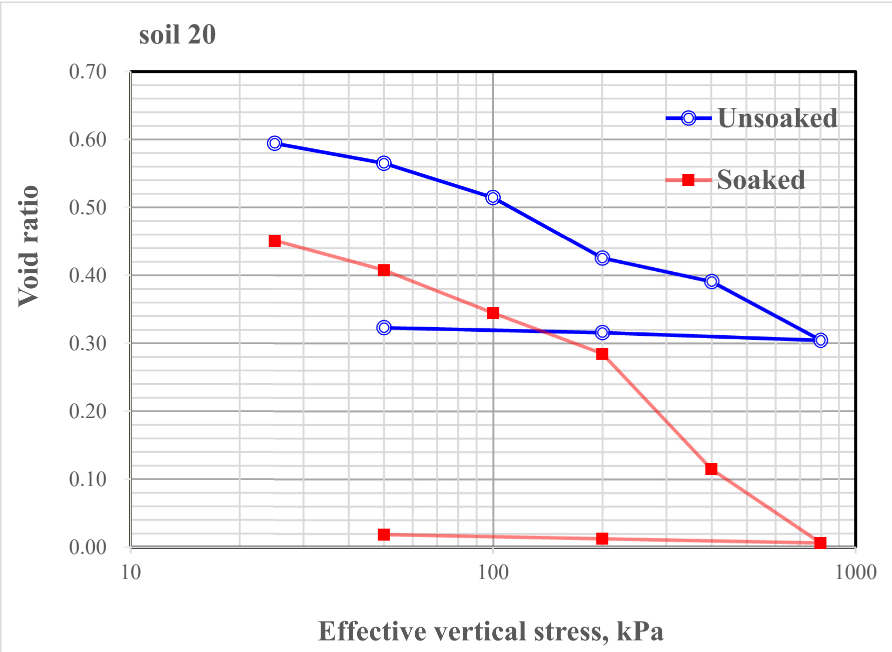

Figure 6. Double oedometer test result for natural (untreated) gypseous soil 20.

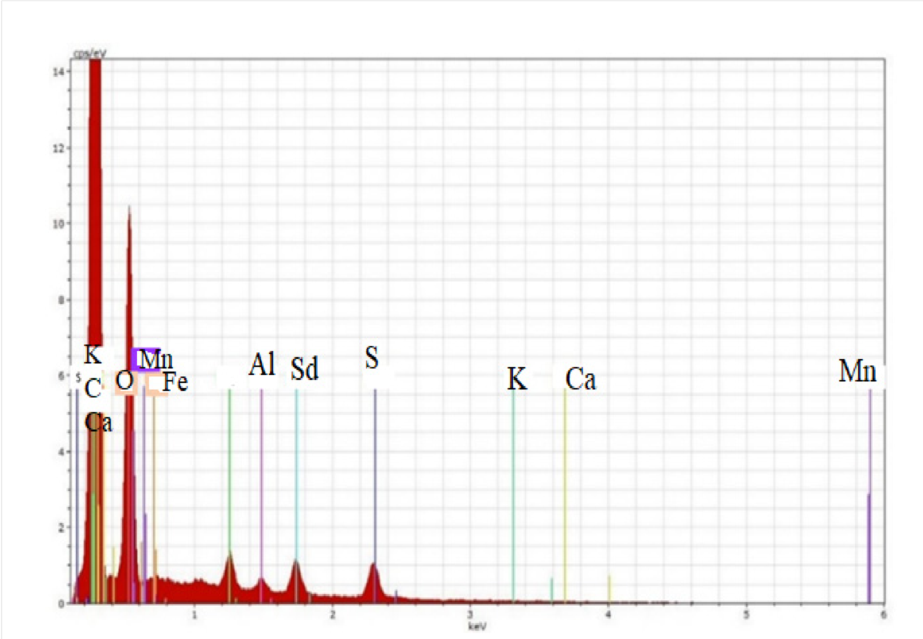

Figure 7. Single oedometer test result for the natural (untreated) gypseous soil 35.

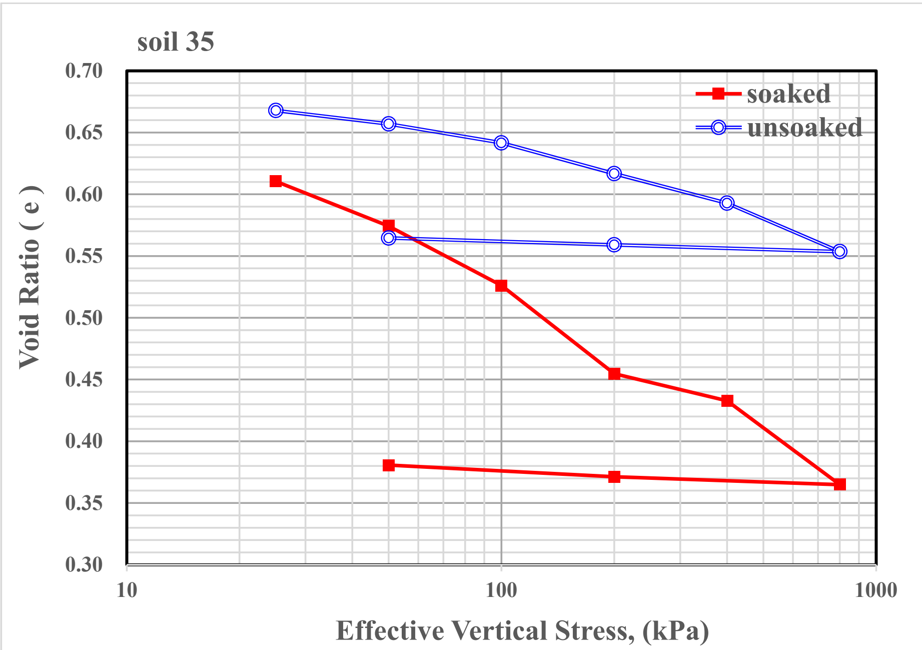

Figure 8. Double oedometer test result for the natural (untreated) gypseous soil 35.

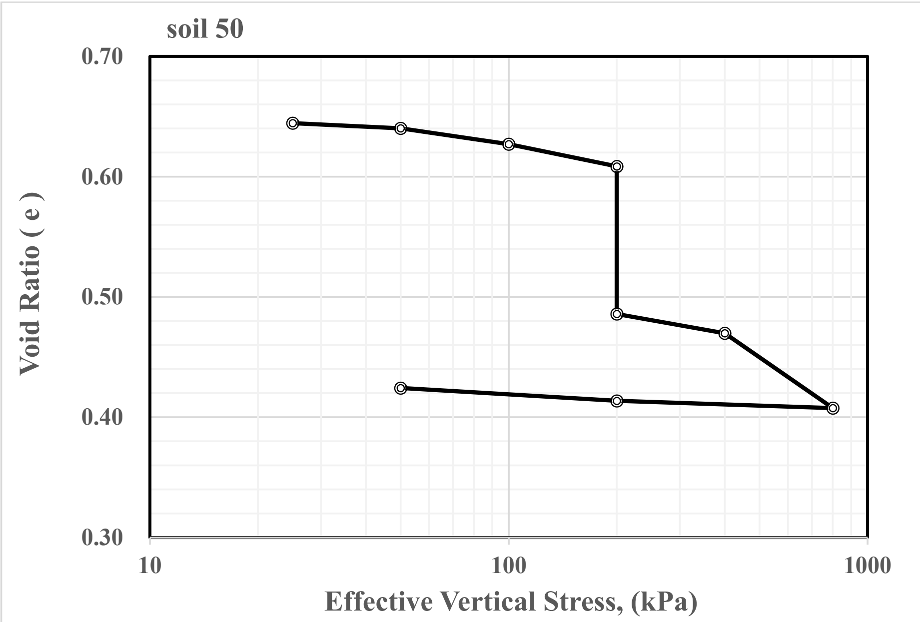

Figure 9. Single oedometer test result for the natural (untreated) gypseous soil 50.

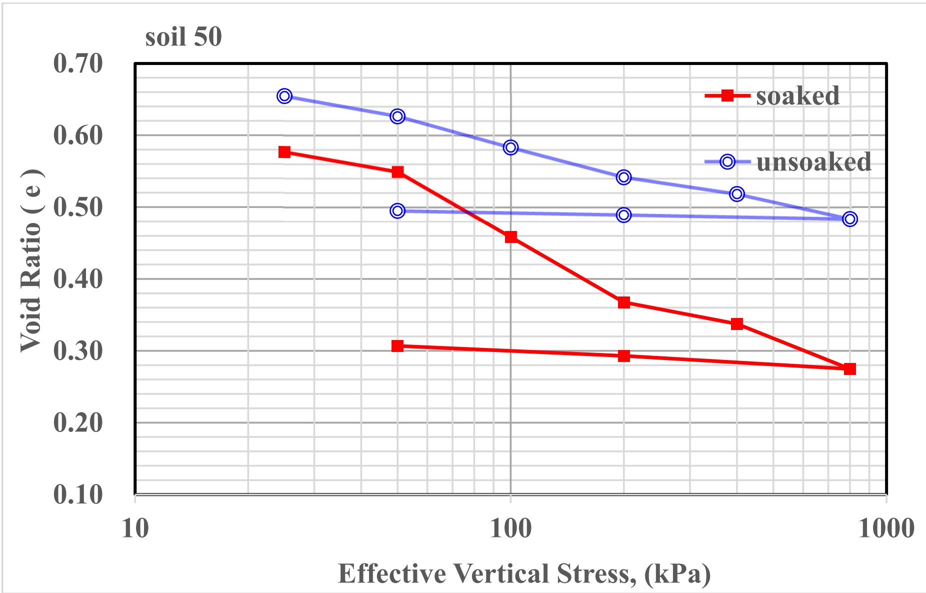

Figure 10. Double oedometer test result for the natural (untreated) gypseous soil 50.

Collapsible soils typically exist in a dry state with unsaturated conditions. This leads to negative pore pressure, which in turn increases the effective stresses and shear strength. In addition, cementing agents like $CaCO_3$ can also help preserve an open and porous structure. When water is added at the (200 kPa) stress level, the pores become less negative, leading to a drop in the shear strength due to reduced effective stresses. In addition, water has the ability to dissolve or weaken the connections between particles, which enables them to be packed more densely. This phenomenon, known as wetting-induced collapse or hydro-compression, can occur with or without additional force. The sudden increase in strain indicated by the vertical line in the figures can be attributed to this phenomenon. The dissolution of gypsum, the realignment of soil particles, and the disturbance of particle cohesion are all variables that influence the susceptibility of gypseous soil to collapse [39].

4.2. Collapse Test Results with Geopolymer

Figures 11–14 and Figures A1–A8 in Appendix A describe the relation between the void ratio and vertical stress, and represent the outcomes of the single-oedometer and double-oedometer tests for the three types of geopolymer-treated gypseous soils. The soil has been treated with three percentages of geopolymer: 2.5%, 5%, and 7.5. Table 6 illustrates the single oedometer test and double oedometer test outcomes, and displays values for the collapse potential for untreated and geopolymer-treated soil. The collapse potential was significantly lower after treatment with geopolymer.

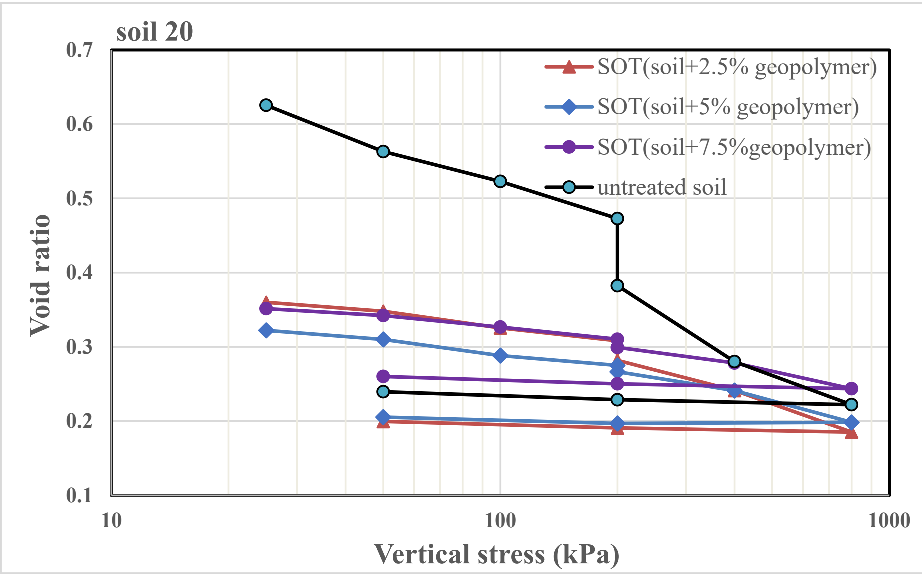

Figure 11. Single oedometer test result for the geopolymer-treated gypseous soil 20.

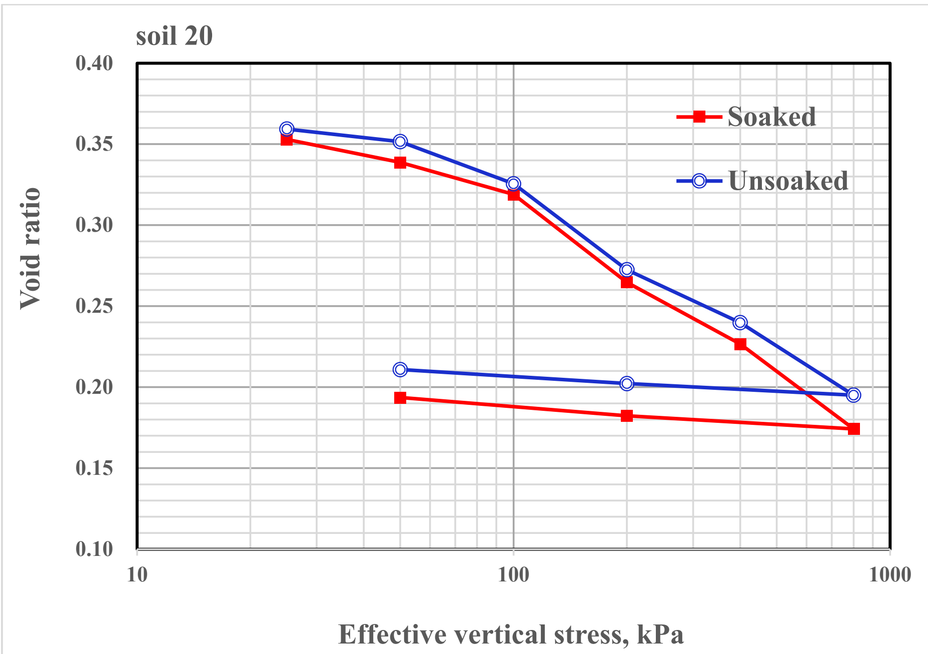

Figure 12. Double oedometer test result for the 2.5% geopolymer-treated gypseous soil 20.

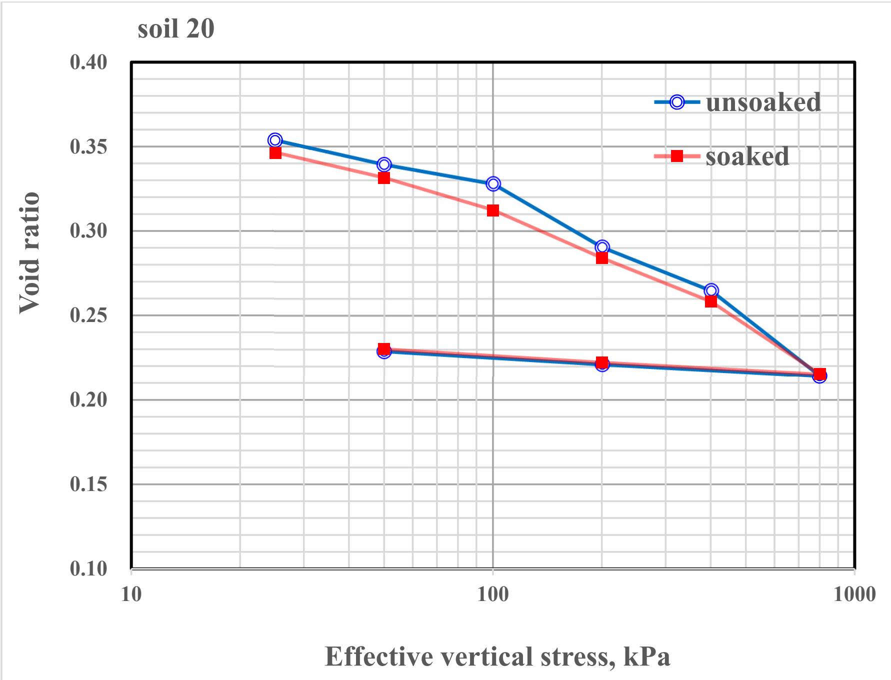

Figure 13. Double oedometer test result for the 5% geopolymer-treated gypseous soil 20.

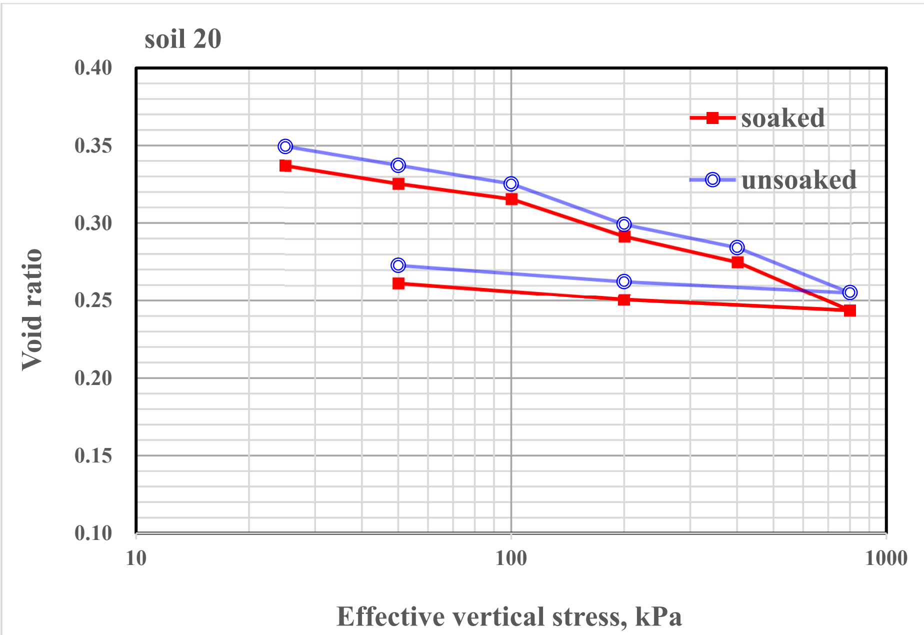

Figure 14. Double oedometer test result for the 7.5% geopolymer-treated gypseous soil 20.

Table 6. Collapse potential for geopolymer-treated and untreated soils.

Soil	Geopolymer %	CP % (SOT)	Efficiency Percentage	Degree of Collapse	CP % (DOT)	Efficiency Percentage	Degree of Collapse
Soil 20	0 (Natural soil)	5.48		moderate	8.52		moderately severe
	2.5	0.99	82	slight	0.57	93.3	slight
	5	0.62	88.7	slight	0.47	94.4	slight
	7.5	0.81	85.2	slight	0.55	93.5	slight
Soil 35	0 (Natural soil)	6.29		moderately severe	9.67		moderately severe
	2.5	0.43	93	slight	0.32	96.7	slight
	5	0.33	94.76	slight	−0.46	104.76	none
	7.5	0.54	91.42	slight	0.47	95.14	slight
Soil 50	0 (Natural soil)	7.35		moderately severe	10.42		severe
	2.5	0.42	94	slight	0.12	98.8	slight
	5	0.40	94.56	slight	0.27	97.41	slight
	7.5	0.17	97.69	slight	0.09	99.14	None

The addition of 2.5% geopolymer concentration reduced the collapse potential of soil 20 to 0.99% and 0.57%; the efficiency percentage in decreasing the collapse potential was 82% and 93.3% for SOT and DOT results, respectively, as shown in Figures 11 and 12. Similarly, for 5% geopolymer concentration, the efficiency was about 88.7% and 94.4%, which was the maximum reduction in collapse potential for this soil (Figures 11 and 13, respectively); for 7.5% geopolymer concentration, the efficiency was 85.2% and 93.5% (Figures 11 and 14, respectively). The collapse potential remained within the range of slight collapse potential.

The collapse potential for soil 35 reduced to 0.43% and 0.32% when 2.5% geopolymer concentration was added, with an efficiency percentage in decreasing the collapse potential of 93% and 96.7% for SOT and DOT results, respectively, as shown in Appendix A Figures A1 and A2. At the same time, the best improvement was 94.76% and 104.76% efficiency for 5% geopolymer concentration (Figures A1 and A3, respectively) and 81.42% and 95.14% for 7.5% geopolymer concentration (Figures A1 and A4, respectively), which were standardized within the range of slight collapse potential and no problem.

As can be shown in Appendix A Figures A5 and A8, the lowest value for soil 50's collapse potential was 0.17% and 0.09% when 7.5% geopolymer concentration was applied, with an efficiency percentage in reducing the collapse potential of 97.69% and 99.14% for SOT and DOT findings, respectively. The efficiency was standardized between the regions with a slight collapse possibility and no problem. In contrast, the efficiency was about 94% and 98.8% for 2.5% geopolymer concentration (Figures A5 and A6, respectively), and 94.56% and 97.41% for 5% geopolymer concentration (Figures A5 and A7, respectively). When water was added to soil 35 samples treated with 5% geopolymer in the double oedometer test, the saturated test revealed a much stronger material than the dry test. Given that this difference displayed a negative collapse potential, it can be concluded that no collapse occurs. The effects of geopolymer concentration on single and double oedometer test collapse potential for soil 20, soil 35, and soil 50 are shown in Figure 15, Figure 16, and Figure 17, respectively.

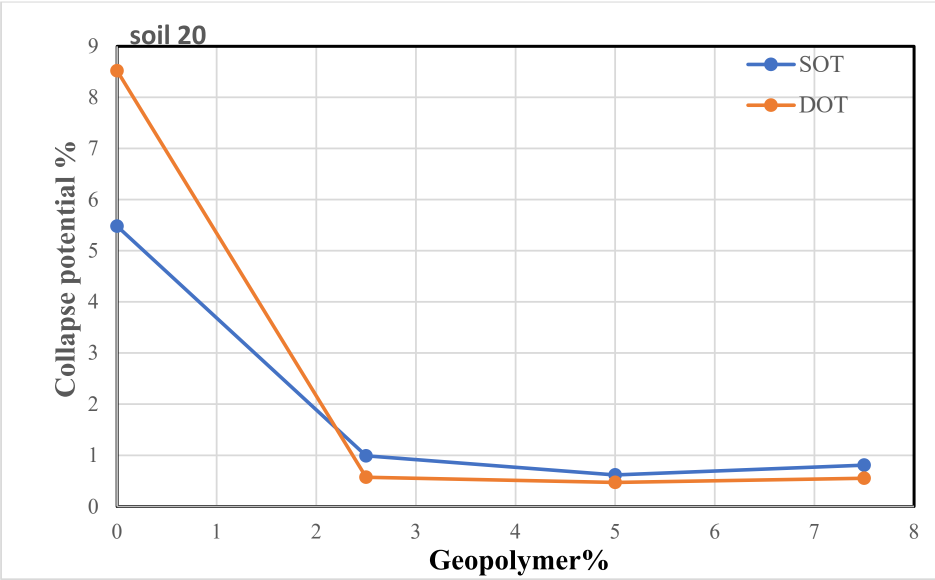

Figure 15. Effect of geopolymer concentration on single and double oedometer test collapse potential for soil 20.

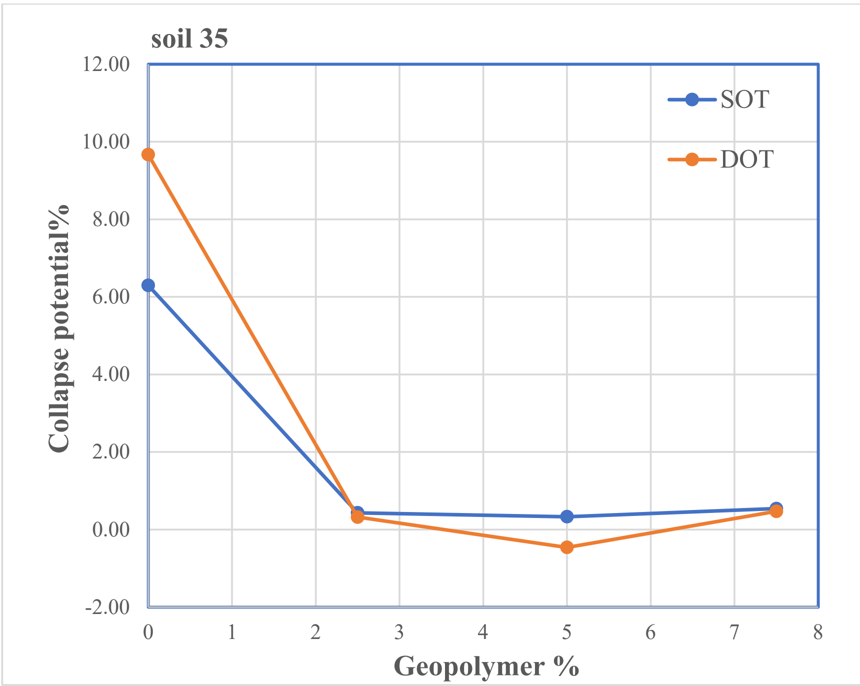

Figure 16. Effect of geopolymer concentration on single and double oedometer test collapse potential for soil 35.

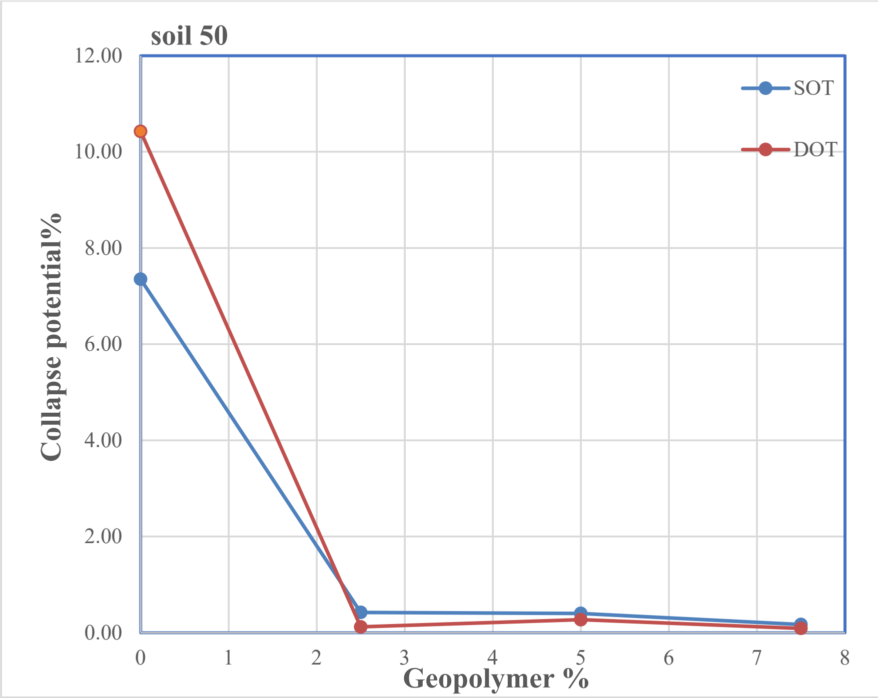

Figure 17. Effect of geopolymer concentration on single and double oedometer test collapse potential for soil 50.

These results unequivocally demonstrate that, at all stress levels, there are reduced voids overall and in initial void ratios compared to untreated specimens. Consequently, compaction raises the dry density and lowers the void ratio, reducing the breakdown of the soil skeleton and the dissolution of gypsum. This causes reduced collapsibility.

The shift in soil suction is what caused the change in collapse potential. The results showed that an increase in the degree of saturation for the soil–sand mixture was correlated with a considerable decrease in the measured total suction; the rate of strength gain decreased as soon as the sand became unsaturated, and when the suction was increased above specific limiting values, the strength actually decreased.

Due to the longer presence of dissolved gypsum in the soil specimen when it is submerged in water at the beginning of the test, it is observed that the collapse potential resulting from the double oedometer test is greater than that in the single collapse test conducted on the untreated natural soil. Contrarily, it has been shown that the collapse potential of geopolymer-treated soil, as determined by double oedometer testing (DOT), is lower than that determined by single oedometer testing (SOT). This suggests that the extended presence of water has a beneficial impact on the geopolymerization process, leading to a more significant decrease in collapse potential values. Furthermore, CCR has the potential to generate Pozzolanic reactions when exposed to water, in addition to its economic and environmental benefits. The presence of Pozzolanic components (Al_2O_3, SiO_2, and Fe_2O_3) in the CCR employed in this study, as shown in Table 3, accounts for roughly 25.71% of its composition. The impact of water, which has not been well investigated in earlier studies, can significantly influence the strength and characteristics of geopolymers. Water in geopolymer mixtures serves not only as a means of dissolving substances, but also affects the interactions between the polymers [40]. The chemical agents, such as Pozzolanic components included in geopolymer, have the highest capacity to create cementation bridges. The intermolecular interactions between particles intensify as the saturation with water increases. Utilizing industrial waste, which reduces environmental issues, is one of the main advantages of geopolymers. Geopolymers, for instance, have remarkable stiffness and compressive strength. Because there is a wide range of inexpensive aluminosilicate materials accessible, industrial byproducts can also be used to create geopolymers.

4.3. Direct Shear Test Results

Figures 18–20 illustrate the results of the direct shear test results for three types of natural untreated gypseous soil. The figures show the relation between the maximum shear stress and the normal stress when specimens of 60 × 60 × 20 mm in size were subjected to normal stresses of 54.5, 109, and 218 kPa. For soil 20, the values of the cohesiveness are equal to 30.14 kPa, and the angle of internal friction is 35.36°. For soil 35, the values of the cohesiveness are equal to 39.06 kPa, and the angle of internal friction is 34.05, while the results for soil 50 were 52.73 kPa for cohesion and 34.11° for the angle of internal friction.

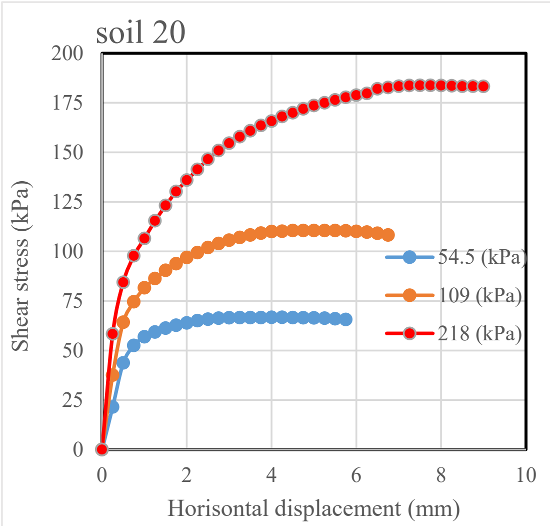

Figure 18. Direct shear test result for natural (untreated) gypseous soil 20.

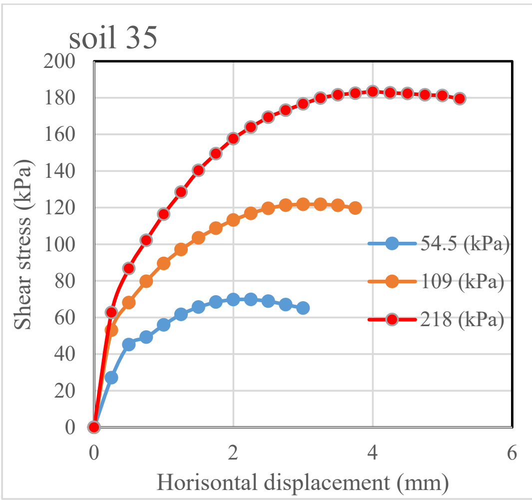

Figure 19. Direct shear test result for natural (untreated) gypseous soil 35.

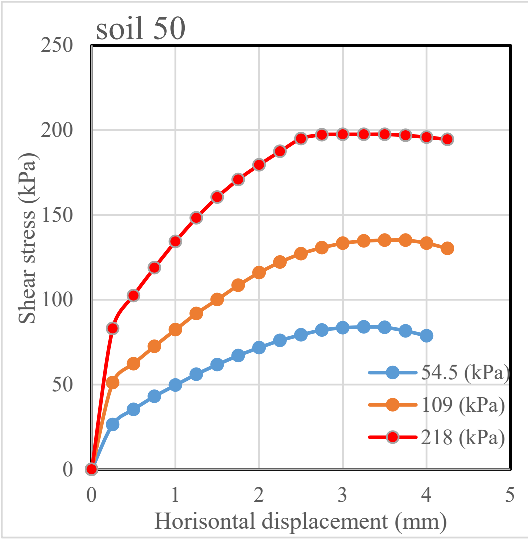

Figure 20. Direct shear test result for natural (untreated) gypseous soil 50.

The direct shear test results for the three types of geopolymer-treated soil are shown in Figures 21–26. Comparing the geopolymer-treated soil samples to the untreated ones, it is clear that the treated ones had a slight reduction in the angle of internal friction and increased cohesion (c). The soil's shear strength increased due to the two parameters working together. This event indicates that the soil's strength has risen, and the geopolymer has helped to connect the soil particles. The addition of 2.5% geopolymer concentration increased the cohesion (c) of soil 20 from 30.14 to 40.54 kPa, with an efficiency percentage of 35%. In comparison, the increasing efficiency in cohesion was about 105% and 158% with 5% and 7.5% geopolymer concentration, respectively. As shown in Figures 24–26, the maximum increase was with 7.5% geopolymer concentration.

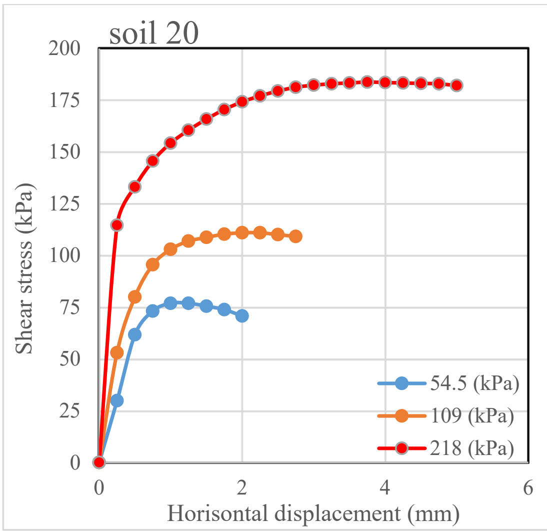

Figure 21. Direct shear test result for 2.5% geopolymer-treated gypseous soil 20.

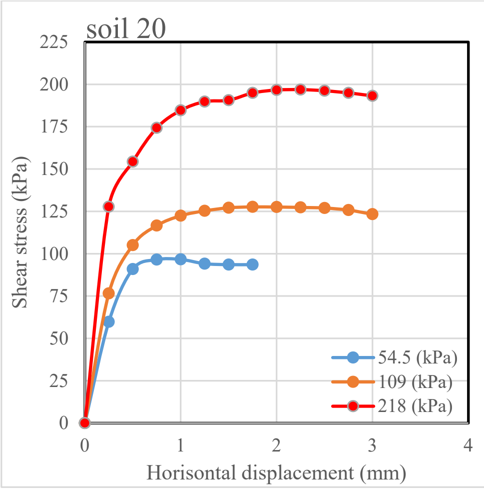

Figure 22. Direct shear test result for the 5% geopolymer-treated gypseous soil 20.

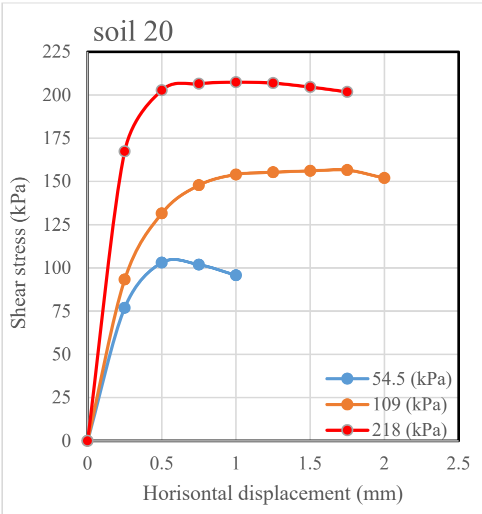

Figure 23. Direct shear test result for the 7.5% geopolymer-treated gypseous soil 20.

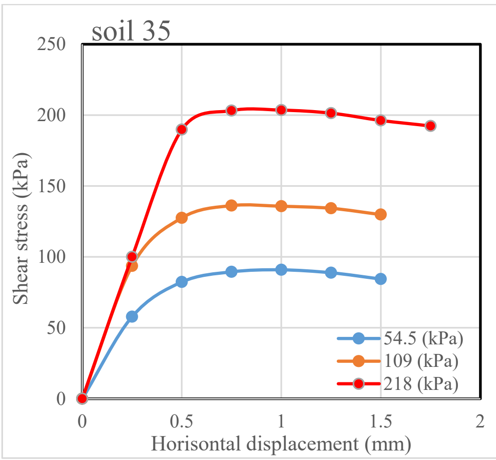

Figure 24. Direct shear test result for the 2.5% geopolymer-treated gypseous soil 35.

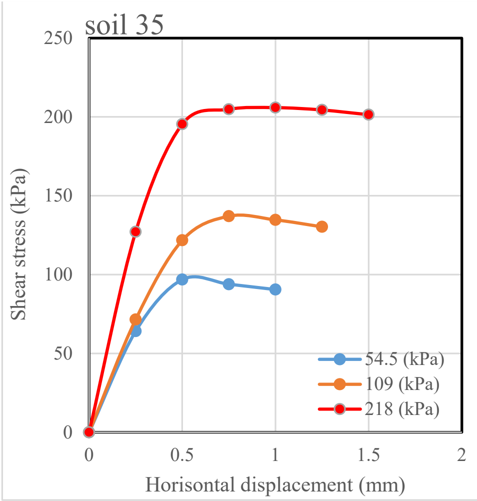

Figure 25. Direct shear test result for the 5% geopolymer-treated gypseous soil 35.

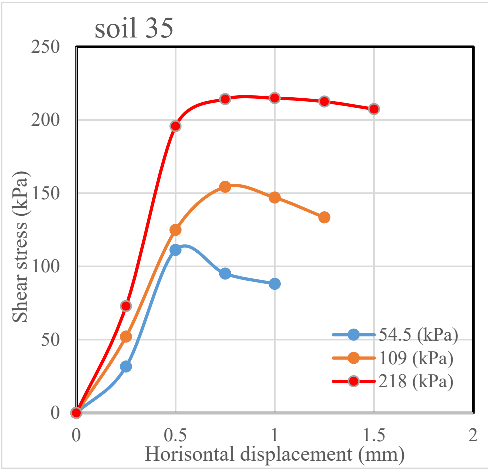

Figure 26. Direct shear test result for the 7.5% geopolymer-treated gypseous soil 35.

For geopolymer-treated soil 35, the cohesion rose from 39.06 kPa to 57.23 kPa by adding 2.5% geopolymer concentration, with a rate increasing up to 46.53%. The increase in cohesion was about 60.24% with 5%, and the maximum increase with an efficiency percentage of 107.24% was with 7.5% geopolymer concentration, as shown in Figures 27–29.

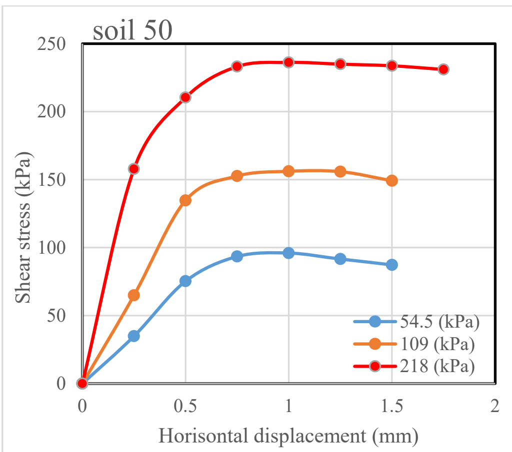

Figure 27. Direct shear test result for the 2.5% geopolymer-treated gypseous soil 50.

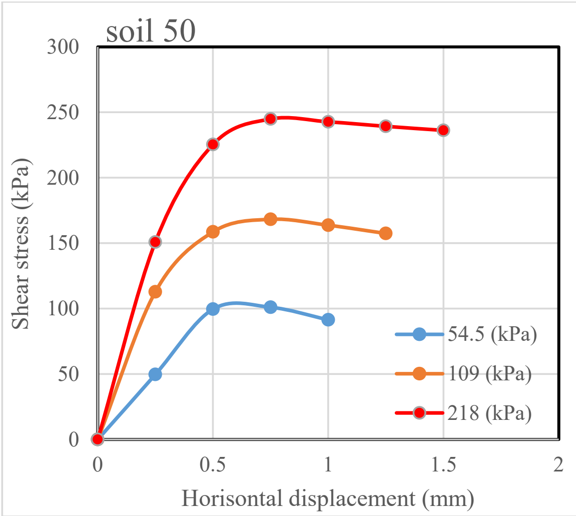

Figure 28. Direct shear test result for the 5% geopolymer-treated gypseous soil 50.

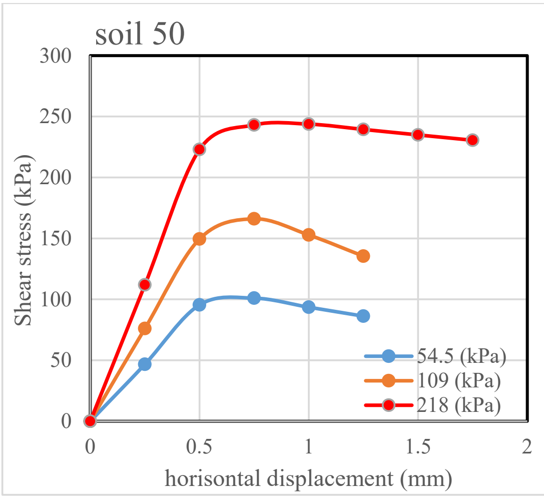

Figure 29. Direct shear test result for the 7.5% geopolymer-treated gypseous soil 50.

In geopolymer-treated soil 50, the cohesion rose slightly from 52.73 kPa to 55.91 kPa by adding 2.5% geopolymer concentration, with a rate increasing up to 6%. The increase in cohesion was about 24% with 5%, and the cohesion value lowered to 62.14 kPa with an efficiency percentage of 18% with 7.5% geopolymer concentration. This soil shows a slight increase in the angle of internal friction, as illustrated in Figures 27–29.

When stabilizing soil with calcium carbide residue (CCR), the changes in shear strength parameters (cohesion and angle of internal friction) are of particular interest. CCR can increase the cohesion of soil due to the chemical reaction between the residue and the soil, often leading to a cementation effect that bonds soil particles together. This enhancement is typically observed in clayey soils where CCR can improve the bonding significantly. While cohesion generally increases, the angle of internal friction might show varied results. Some studies indicated a slight increase in the friction angle due to densification, while others found that it remained relatively constant depending on the soil type. For sandy soils, the friction angle might see less improvement than cohesion. Shear strength improvement has a peak at a specific CCR content. Excessive CCR can lead to diminishing returns, or even a decrease in strength, due to the formation of weak calcium compounds that may compromise the bonding.

Based on the findings of the direct shear test illustrated in Table 7, all gypseous soils have a cohesiveness value; this could be because, in the case of the untreated gypseous soil, the gypsum acts as a cement, and in the case of the treated gypseous soil, both the gypsum and geopolymer function as a cement.

Table 7. Direct shear test results for geopolymer-treated and untreated soils.

Soil	% Geopolymer	Normal Stress (kPa)	Shear Stress (kPa)	Cohesion (kPa)	Efficiency Percentage (%)	Angle of Internal Friction (Deg)	Efficiency Percentage (%)
Natural soi 20	0	54.5	66.75	30.14		35.36	
		109	110.53				
		218	183.77				
Geopolymer-treated soil 20	2.5	54.5	76.93	40.54	35	33.24	−6.0
		109	110.99				
		218	207.39				
	5	54.5	96.65	61.84	105	31.76	−10
		109	127.66				
		218	197.31				
	7.5	54.5	103.05	77.63	158	31.54	−11
		109	156.54				
		218	207.39				
Natural soil 35	0	54.5	69.84	39.06		34.05	
		109	121.76				
		218	183.34				
Geopolymer-treated soil 35	2.5	54.5	90.90	57.23	46.53	34.16	0.35
		109	136.18				
		218	203.53				
	5	54.5	96.88	62.59	60.24	33.48	−1.66
		109	137.29				
		218	205.89				
	7.5	54.5	111.21	80.94	107.24	31.92	−6.24
		109	154.37				
		218	214.91				
Natural soil 50	0	54.5	83.94	52.73		34.11	
		109	135.08				
		218	197.52				
Geopolymer-treated soil 50	2.5	54.5	95.97	55.91	6	40.04	17.40
		109	156.11				
		218	243.81				
	5	54.5	103.51	65.19	24	40.09	17.52
		109	168.25				
		218	244.90				
	7.5	54.5	101	62.14	18	40.38	18.40
		109	166.09				
		218	243.81				

The incorporation of geopolymer materials into gypseous soil can significantly enhance its strength and durability. Gypseous soils, which contain gypsum (calcium sulfate), are known for their high solubility in water, causing strength loss, settlement issues, and collapsibility when exposed to moisture. Geopolymer additives, typically produced from aluminosilicate sources activated by alkaline solutions, help to mitigate these weaknesses.

Here is a breakdown of the effects of geopolymer on the strength of gypseous soils:

- Geopolymer binders improve the compressive strength of gypseous soils by creating a strong matrix that binds the soil particles together.
- The geopolymer reaction forms aluminosilicate bonds that increase soil density and cohesion, leading to higher load-bearing capacity.

Geopolymer-treated soils exhibit lower solubility in water due to the stable aluminosilicate network. The durability of gypseous soils improves as the geopolymer treatment limits the dissolution of gypsum, reducing strength loss in the presence of moisture. Geopolymer stabilization enhances the internal friction angle and cohesion of the soil, making it less susceptible to shearing under loads. This improvement in shear strength also mitigates issues like erosion and collapse when the soil is exposed to external stresses.

Geopolymer treatment reduces the swelling and shrinkage behavior common in gypseous soils when moisture levels change. The stabilized soil exhibits less volume change, which is critical in maintaining structural stability and reducing settlement in foundations. The presence of gypsum in soil can cause sulfate attacks on concrete and other building materials, but geopolymer stabilization forms a sulfate-resistant matrix. This sulfate-resistant property prevents further degradation and enhances soil longevity.

5. Conclusions

The following conclusions can be made in light of the experimental findings and comparison with earlier studies:

1. The outcomes of the collapse potential tests demonstrate that the adequate geopolymer percentage was found to be 5% for soil 20 and soil 35 since it reduced the collapse potential for soil 20 by 88.6% and 94.4%, respectively, and for soil 35 by 94.76% and 104.76% for SOT and DOT, respectively, compared with the natural soil.
2. The collapse potential tests revealed that the adequate geopolymer percentage was found to be 7.5% for soil 50, which includes high gypsum content of 50%, since it reduced the collapse potential by about 98% and 105% for SOT and DOT, respectively, compared with the natural untreated soil.
3. Soil containing 35% gypsum, with a moderate gypsum content, shows the maximum reduction in the collapse potential after treatment with 5% geopolymer.
4. The shear strength tests demonstrate a slight reduction in the angle of internal friction and increased cohesion (c) with an increase in geopolymer content, but the soil's shear strength increased due to the two parameters working together. The adequate geopolymer percentage for soil 20 and soil 35 was found to be 7.5% since it increased the cohesion for soil 20 and soil 35 by 158% and 107%, respectively, compared with the natural soil.
5. The direct shear test demonstrates that the adequate geopolymer percentage was found to be 5% for soil 50 since it increased the cohesion by 24% compared with the natural soil.
6. Soil containing 20% gypsum, with the lowest gypsum content, shows the maximum increased cohesion after treatment with 7.5% geopolymer.

Overall, adding geopolymers to gypseous soil creates a stabilized, cohesive structure that improves compressive and shear strength, reduces solubility, and enhances durability against environmental factors. The specific improvements depend on the type and concentration of the geopolymer, soil composition, and treatment method used.

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Conflicts of Interest: The authors have no conflict of interest.

Appendix A. Collapse Test Results with Geopolymer for Soil 35 and Soil 50

Appendix A.1. Collapse Test Results with Geopolymer for Soil 35

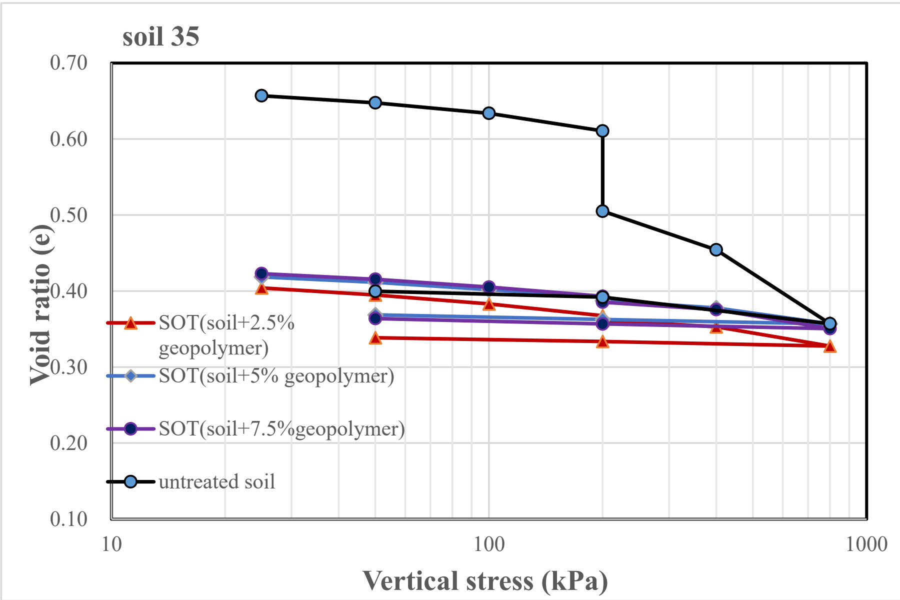

Figure A1. Single oedometer test result for the geopolymer-treated gypseous soil 35.

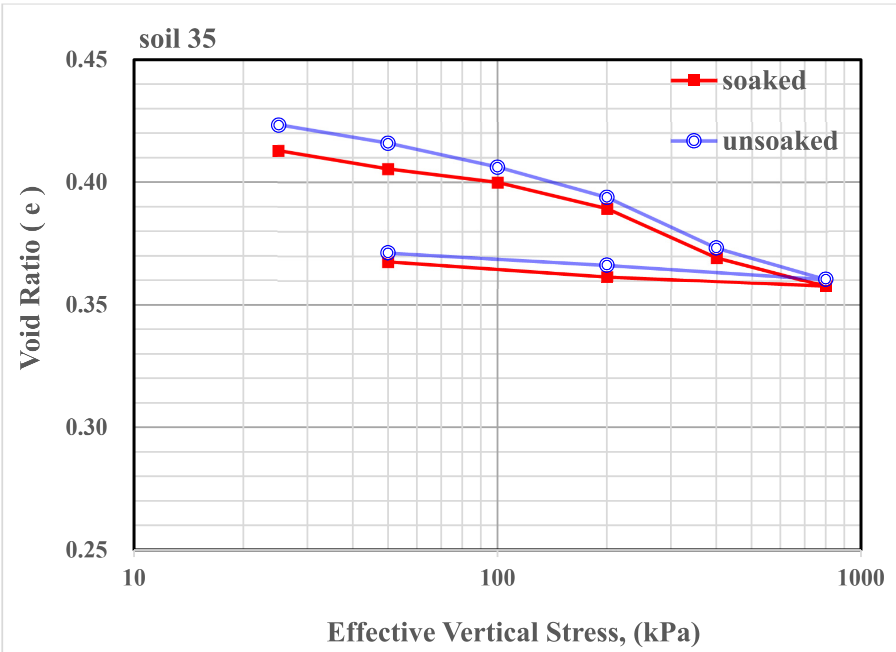

Figure A2. Double oedometer test result for the 2.5% geopolymer-treated gypseous soil 35.

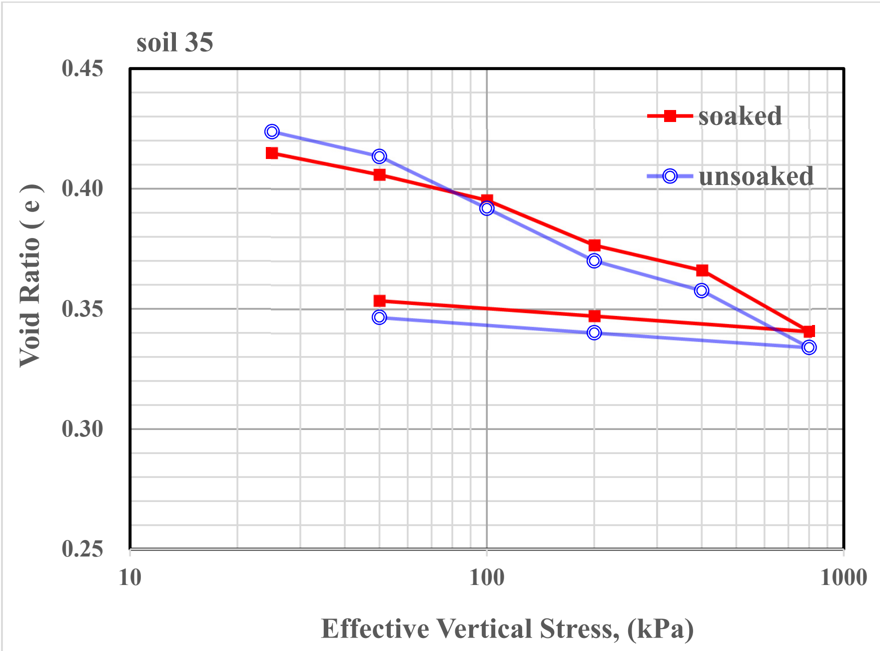

Figure A3. Double oedometer test result for the 5% geopolymer-treated gypseous soil 35.

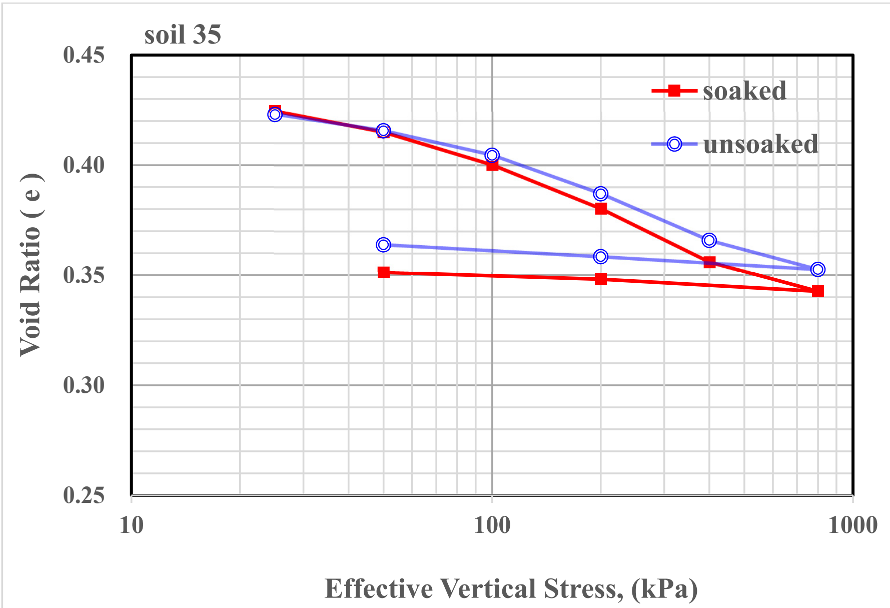

Figure A4. Double oedometer test result for the 7.5% geopolymer-treated gypseous soil 35.

Appendix A.2. Collapse Test Results with Geopolymer for Soil 50

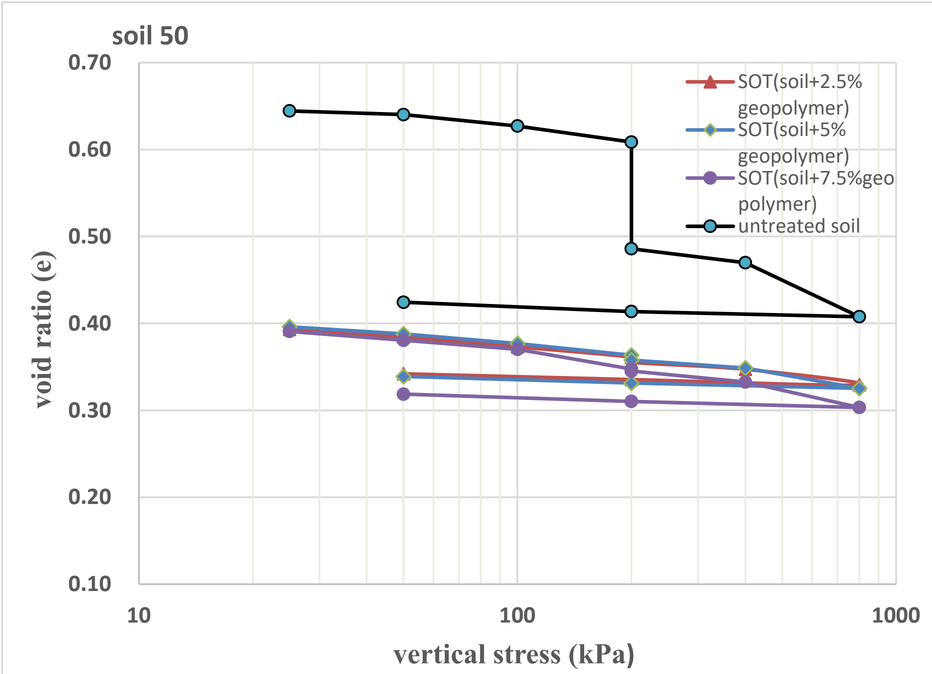

Figure A5. Single oedometer test result for the geopolymer-treated gypseous soil 50.

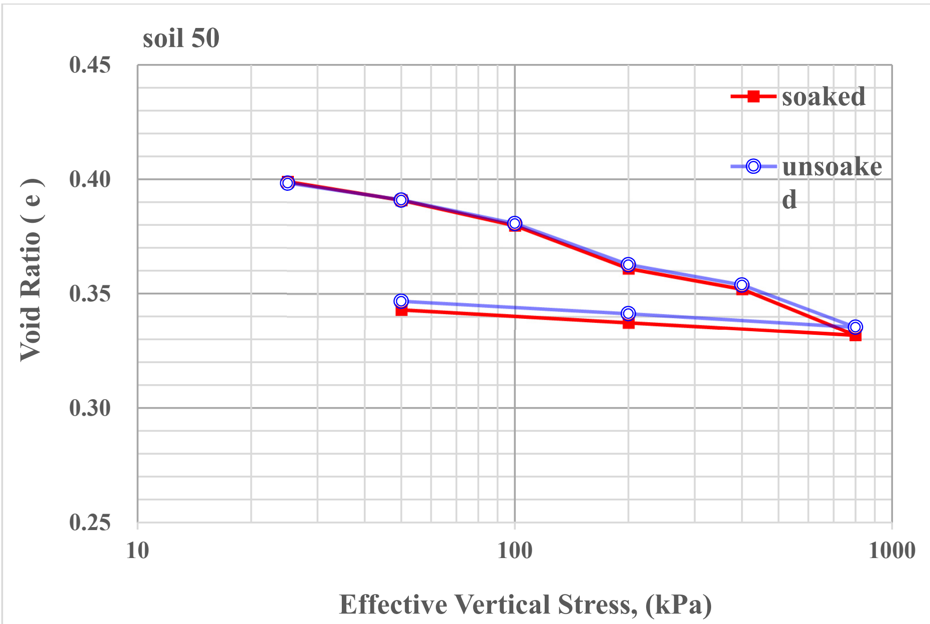

Figure A6. Double oedometer test result for the 2.5% geopolymer-treated gypseous soil 50.

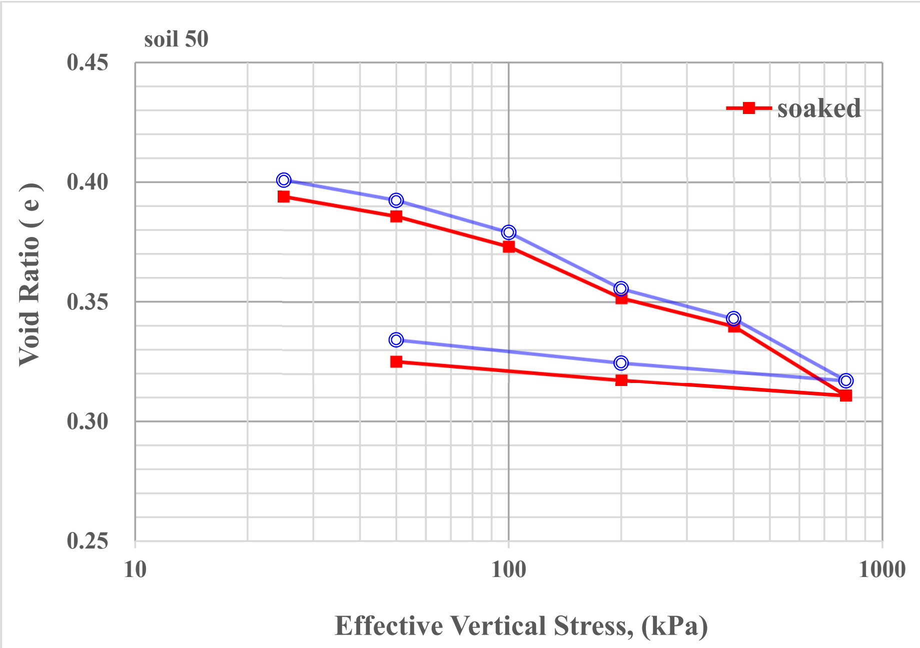

Figure A7. Double oedometer test result for the 5% geopolymer-treated gypseous soil 50.

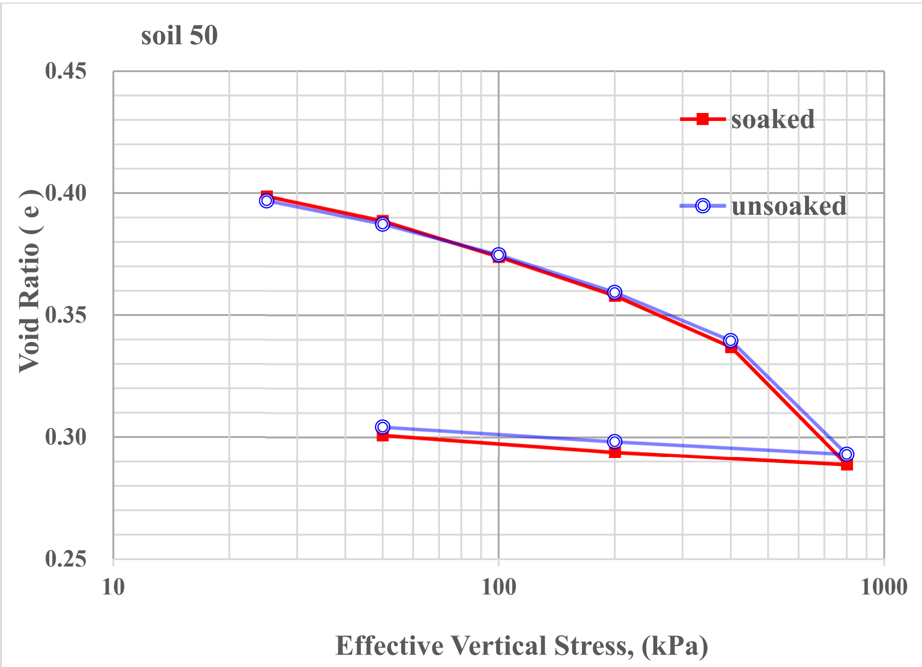

Figure A8. Double oedometer test result for the 7.5% geopolymer-treated gypseous soil 50.

References

1. FAO. *Managements of Gypsiferous Soils*; Food and Agriculture Organization of the United Nations: Rome, Italy, 1990.
2. Fattah, M.Y.; Obead, I.H.; Omran, H.A. A study on leaching of collapsible gypseous soils. *Int. J. Geotech. Eng.* **2022**, *16*, 44–54. [CrossRef]
3. Al-Obaidi, Q.A.J. Hydro-Mechanical Behaviour of Collapsible Soils. Ph.D. Thesis, Civil and Environmental Engineering Ruhr-Universität Bochum, Bochum, Germany, 2015.
4. Solis, R.; Zhang, J. Gypsiferous soils: An engineering problem. In Proceedings of the Sinkholes and the Engineering and Environmental Impacts of Karst, Tallahassee, FL, USA, 22–26 September 2008; pp. 742–749.
5. Al-Obaidi, A.A.; Al-Mafragei, I. Settlement and collapse of gypseous soils. *Tikrit J. Eng. Sci.* **2016**, *23*, 20–31. [CrossRef]
6. Al-Obaidi, A.; Najem, S. Improvement of Gypseous Soils Using Different Types of Geosynthetic Materials. In Proceedings of the 2nd International conference Geosynthetics Middle East, Dubai, United Arab Emirates, 10–11 November 2009.

7. Al-Zory, E. The Effect of Leaching on Lime Stabilized Gypseous Soil. Master's Thesis, University of Mousl, Mousl, Iraq, 1993.
8. Al-Morshedy, A. The Use of Cut-Back MC-30 for Controlling the Collapsibility of Gypseous Soils. Master's Thesis, Building and Construction Department, University of Technology, Baghdad, Iraq, 2001.
9. Al-Alawee, A. Treatment of Al-Therthar Gypseous Soil by Emulsified Asphalt Using Mold Test. Master's Thesis, Building and Construction Department, University of Technology, Baghdad, Iraq, 2001.
10. Fattah, M.Y.; Al-Musawi, H.H.; Salman, F.A. Treatment of collapsibility of gypseous soils by dynamic compaction. *Geotech. Geol. Eng.* **2012**, *30*, 1369–1387. [CrossRef]
11. Fattah, M.Y.; Al-Ani, M.M.; Al-Lamy, M.T.A. Treatment of collapse of gypseous soils by grouting. *Proc. Inst. Civ. Eng.-Ground Improv.* **2013**, *166*, 32–43. [CrossRef]
12. Ibrahim, A.; Schanz, T. Improvement of gypsiferous soil strength by silicone oil. *Soil Mech. Found. Eng.* **2017**, *54*, 117–121. [CrossRef]
13. Abbas, J.K.; Al-Luhaibi, H.M. Influence of Iron Furnaces Slag on Collapsibility and Shear Strength of Gypseous Soil. *Tikrit J. Eng. Sci.* **2020**, *27*, 65–71. [CrossRef]
14. Aswad, M.F.; Al Gharbawi AS, A.; Fattah, M.Y.; Mustfa, R.H.; Hameed, H.R. Improvement of Clayey Soil Characteristics Using Poly Acrylamide Geopolymer. *Transp. Infrastruct. Geotechnol.* **2023**, *11*, 1673–1690. [CrossRef]
15. Xi, Y.; Sun, M.; Li, H.; Li GWang, P.; Li, L. Study on the Shear Strength of Loess Solidified by Guar Gum and Basalt Fiber. *Materials* **2024**, *17*, 3116. [CrossRef]
16. Theyab, A.F.; Muhauwiss, F.M.; Alabdraba, W.M. Effects of xanthan gum biopolymers on gypseous soils characteristics. *Tikrit J. Eng. Sci.* **2020**, *27*, 22–28. [CrossRef]
17. Al-Gharrawi, A.M.B.; Hayal, A.L.; Fattah, M.Y. Collapse Problem Treatment of Gypseous Soil by Nanomaterials. *Int. J. Eng.* **2020**, *33*, 1737–1742. [CrossRef]
18. Makaratat, N.; Jaturapitakkul, C.; Laosamathikul, T. Effects of calcium carbide residue–Fly ash binder on mechanical properties of concrete. *J. Mater. Civ. Eng.* **2010**, *22*, 1164–1170. [CrossRef]
19. Bao, H.; Liu, C.; Lan, H.; Yan, C.; Li, L.; Zheng, H.; Dong, Z. Time-dependency deterioration of polypropylene fiber reinforced soil and guar gum mixed soil in loess cut-slope protecting. *Eng. Geol.* **2022**, *311*, 106895. [CrossRef]
20. Bekkouche, S.R.; Benzerara, M.; Zada, U.; Muhammad, G.; Ali, Z. Use of Eco-Friendly Materials in the Stabilization of Expansive Soil. *Buildings* **2022**, *12*, 1770. [CrossRef]
21. Chindaprasirt, P.; Jitsangiam, P.; Horpibulsuk, S. Performance and evaluation of calcium carbide residue stabilized lateritic soil for construction materials. *Case Stud. Constr. Mater.* **2020**, *13*, e00389. [CrossRef]
22. Kampala, A.; Horpibulsuk, S.; Prongmanee, N.; Chinkulkijniwat, A. Influence of wet-dry cycles on compressive strength of calcium carbide residue–fly ash stabilized clay. *J. Mater. Civ. Eng.* **2014**, *26*, 633–643. [CrossRef]
23. Afzali, M.H. Sustainable Utilization of Calcium Carbide Residue along with Polypropylene Fiber Waste Materials for Accessing Swelling and Strength Characteristics of Black Cotton Soil. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1110*, 012003. [CrossRef]
24. Alsafi, S.; Farzadnia, N.; Asadi, A.; Huat, B.K. Collapsibility potential of gypseous soil stabilized with fly ash geopolymer; characterization and assessment. *Constr. Build. Mater.* **2017**, *137*, 390–409. [CrossRef]
25. *ASTM D422-63*; Standard Test Method for Particle-Size Analysis of Soils. ASTM Standards: West Conshohocken, PA, USA, 2007.
26. *ASTM D854-23*; Standard Test Methods for Specific Gravity of Soil Solids by the Water Displacement Method. American Society for Testing and Materials: West Conshohocken, PA, USA, 2023.
27. *ASTM D2216-19*; Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. American Society for Testing and Materials: West Conshohocken, PA, USA, 2023.
28. *ASTM D4318-17*; Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. American Society for Testing and Materials: West Conshohocken, PA, USA, 2023.
29. Al-Mufty, A.; Nashat, I. Gypsum content determination in gypseous soils and rocks. In Proceedings of the 3rd International Jordanian Conference on Mining, Amman, Jordan, 4–11 October 2000.
30. *ASTM D698-21*; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)). American Society for Testing and Materials: West Conshohocken, PA, USA, 2023.
31. *ASTM D1556-15*; Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method. American Society for Testing and Materials: West Conshohocken, PA, USA, 2023.
32. *BS 1377-2:1990*; Methods of Test for Soils for Civil Engineering Purposes. British Standards Institution: London, UK, 1990.
33. *ASTM D2487-17*; Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). American Society for Testing and Materials: West Conshohocken, PA, USA, 2023.
34. *ASTM D5333-03*; Standard Test Method for Measurement of Collapse Potential of Soils. Annual book of ASTM standards; ASTM Standards: West Conshohocken, PA, USA, 2003; 4p.
35. *ASTM D3080-11*; Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. Annual book of ASTM standards; ASTM Standards: West Conshohocken, PA, USA, 2003; 4p.
36. Horpibulsuk, S.; Kampala, A.; Phetchuay, C.; Udomchai, A.; Arulrajah, A. Calcium carbide residue–A cementing agent for sustainable soil stabilization. *Geotech. Eng. J. SEAGS AGSSEA* **2015**, *46*, 22–27.
37. Dolganova, I.O.; Dolganov, I.M.; Bunaev, A.A.; Pasyukova, M.A. Nature of highly viscous component in the alklybenzene sulfonic acid technology and its influence on the process efficiency. *Pet. Coal* **2019**, *61*, 25–31.

38. Seleam, S. Geotechnical Characteristics of a Gypseous Sandy Soil Including the Effect of Contamination with Some Oil Products. Master's Thesis, University of Technology, Baghdad, Iraq, 1988.
39. Xie, J.; Kayali, O. Effect of initial water content and curing moisture conditions on the development of fly ash-based geopolymers in heat and ambient temperature. *Constr. Build. Mater.* **2014**, *67*, 20–28. [CrossRef]
40. Mymrin, V.A.; Vázquez-Vaamonde, A.J. Red mud of aluminium production waste as basic component of new construction materials. *Waste Manag. Res.* **2001**, *19*, 465–469. [CrossRef] [PubMed]