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Geotechnical Behaviour of Gypseous Soil Treated by Geopolymer Additives

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ABSTRACT

Gypseous soil is well-known for its numerous engineering problems. When this soil is exposed to water, the gypsum in the soil dissolves, causing the buildings built on it to collapse; so, treating gypseous soil is important for improving its engineering characteristics. The present paper focuses on studying the effect of adding geopolymer on mechanical characteristics of gypseous soil. This study presents the results obtained from a series of experimental tests, including direct shear, consolidation, and collapsibility tests. Tests were conducted on samples of gypseous soil taken from depth 1.5 meters below ground level with gypsum content of 41%. The geopolymer was used in three different molarities for the collapse test (10M, 12M, and 14M) and a 14 molarity only for the shear and consolidation tests, where equal proportions of fly ash were combined with an alkaline activator that was composed of sodium hydroxide and sodium silicate. The binder (fly ash + alkaline) to the soil was added to the treated samples during mixing at a rate of 20% by weight. The findings showed that treating the soil with geopolymer leads to a notable enhancement in the angle of internal friction of the soil particles from (37 to 42) degrees. as well as a reduction in the soil compressibility and a reduction in the susceptibility of the soil to collapse, with an improvement degree of 64% when using a geopolymer with a molarity of 14 M. This improvement was achieved by using a geopolymer with a higher concentration of NaOH. The best results were achieved when a geopolymer with a molarity of 14 was used, which is the ideal ratio.

1. Introduction

Gypseous soils are collapsible soils consisting of hydrated calcium sulfate ($CaSO_4.2H_2O$). Gypsum dissolves owing to water table fluctuation or infiltration into gypseous soils, leading the soil to be soft and extremely compressible, generating significant foundation issues due to the soil's structure collapsing and the creation of cavities [1]. The amount of gypsum in the soil is a difficult problem for geotechnical engineers when building on or above this kind of soil [2]. Gypseous soil is hard when it is dried, but it loses its strength when it becomes saturated with water, leading the soil structure to break down and become compressible. Wetting or immersing gypseous soils dissolves the calcite silicate cementing the soil particles, thereby weakening the bindings between soil particles [3,4]. Figure 1 shows the distribution of gypsum in Iraq according to Barzanji [5]. Many factors influence the rate of gypsum dissolving, including the gypsum concentration, temperature, air pressure, etc [6]. Construction projects on gypseous soils have a long history of

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settlement issues, including but not limited to buildings, roads, bridges, waterways, ports, and railways. Loss of cementation between particles of soil happens due to the breakdown of gypsum when the water table or rainfall changes and/or infiltrates into gypseous soils [7]. There are several techniques for treating gypseous soil, including soil replacement, injection, and the use of additives. Several researchers attempted to examine the effect of various additions on the behavior of gypseous soils.

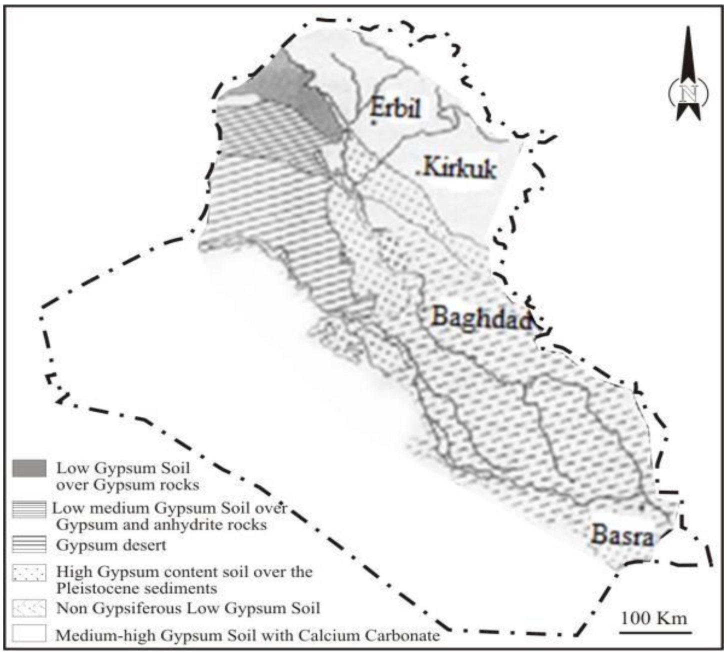


Figure 1. The distribution of gypsum in Iraq [5]

Al-Zory [8] demonstrated that adding 5-7% lime with gypseous soil containing 43% gypsum increased the soil's strength and resistance to leaching. It has been stated that after 28 days of curing, the soil became essentially impermeable. Moayyeri [9] found that adding 1% of silica fume and lime increased the unconfined compressive strength of gypseous soil by 15 times. Direct shear tests showed that combining silica and lime improved mechanical characteristic of gypseous soil. Ibrahim [10] examined the enhancement of gypseous soil properties through the use of silicone oil to mitigate the water's influence on these soils. Aziz [11] focuses on the suitability of fuel oil for enhancing gypsous soil. Esho [12] investigated how lime and emulsion asphalt may be used to stabilize gypseous soil. Fattah [13] investigated the compressibility of four kinds of gypseous soils under different conditions. They grouted specimens with acrylate, which reduced collapsibility by more than 50% to 60% and reduced compressibility by over 60-70%. The acrylate liquid also changed the soil's shear strength characteristics by improving cohesion and reducing the internal friction angle. Mohsen [14] examined the bearing capacity of the gypseous soil before and after it was reinforced with geotextile layers. The results revealed a significant increase in bearing capacity and volume change when employing the triple phase pattern with an increase in permissible bearing capacity for reinforced gypseous soil. In most cases, Ordinary Portland Cement may be used to enhance any soil type. Excessive cement in soils causes water to evaporate during hardening, leading to noticeable dimension shrinkage and cracking [15]. In addition, a lot of carbon dioxide is always released throughout the cement manufacturing process, which adds to the worldwide environmental pressure [16]. Geopolymers are Portland cement-competing materials that utilize industrial solid wastes of aluminosilicate composition in conjunction with an alkaline activator. They have a high mechanical strength, a fast setup time, and a long lifespan. Furthermore, they are low-cost, produce less carbon dioxide during synthesis, and hence have a significantly reduced influence on global warming. Given these benefits, geopolymers are being investigated as prospective alternative materials that may be used in a variety of fields [17]. Scientifically, a geopolymer is a substance made of alkali aluminosilicate. Formed by reacting an aluminosilicate solid with a very concentrated aqueous alkali hydroxide or silicate solutions [18]. Using geopolymers as stabilizers of soil has been a topic of research in recent years [19]. A more dense microstructure formed between soil particles with the use of a geopolymer binder, improving the soil's volume stability and mechanical characteristics [20], As a result, the geopolymer may be used for both shallow- and deep-depth soil stabilization (e.g., in the pavement's base or subbase, embankment, shallow foundations, airport building, etc.) [21–24]. According to the researcher's knowledge, geopolymer has not been used to enhance the properties of gypseous soil, the aim of this study is to improve the mechanical properties of gypseous soil by examining the compressibility, collapsibility, and strength characteristics of soil before and after undergoing geopolymer treatment.

2. Materials and methods

For this study, the soil was taken at a depth of 1.5 meters in Tikrit, Iraq, its gypsum content, as reported in Table 1, is around 41%. Fly ash (FA) has been provided, the chemical composition of fly ash as analyzed by X-ray fluorescence (XRF) is summarized in Table 2. In FA, the total quantity of the main components SiO_2, Al_2O_3, and Fe_2O_3 is 77.74 Accordance to ASTM C-618 [25], it is considered to be fly ash of the class F kind. Figure 2 presented the particle size distribution curve of soil and FA, which was employed as a precursor to creating the majority of the geopolymer (geo). In order to create an alkaline activator, a mixture consisting of powdered sodium hydroxide (NaOH) and a sodium silicate solution (Na_2SiO_3) was utilized, NaOH with a purity of (97-99) % was diluted in water to reach the required molar (M) concentration before being mixed with sodium silicate. To produce geopolymer an alkaline activator (sodium hydroxide with sodium silicate) is prepared and then combined with the necessary quantity of fly ash about 24 hours before use. In this study, a geopolymer of varying molarities was utilized.

2.1 Direct shear test

Shear strength, such as other geotechnical characteristics, is important in the design and construction of buildings. When any civil engineering application comes into contact with soils, shear strength is frequently important. The shear resistance is an important consideration throughout the building of standing building equipment and at the finish of the construction process while supporting the building [26]. A geopolymer with a molarity of 14 M was employed, and the fly ash was blended with an alkaline at a 1:1 (fly ash: alkaline) ratio. The binder (fly ash + alkaline) to the soil was 20% by weight was added to the treated samples during mixing. Treated soil samples were placed in nylon bags for curing for seven days after being compressed in a shear box measuring (60*60*20) mm, the treated and untreated soil samples were compacted at 80% of the maximum dry unit weight. Using the direct shear equipment and the method specified in (ASTM D3080) [27], the shear test was conducted. The shear strength parameters (C and Ø) at saturation condition were calculated from the shear stress-normal stress curve using a calibrated proving ring with a load capacity of 2 KN, a strain rate of 0.2 mm/min, as well as a normal stress of (56,112,224) kPa.

2.2 Consolidation test

The experiment was conducted in accordance with the procedures specified in ASTM D-2435 [28]. Using soil samples that are both in their natural state and have undergone treatment. A geopolymer solution with a concentration of 14 molarity was utilized in the preparation of the treated sample. Equal amounts of fly ash and an alkaline activator were combined in a 1:1 ratio. The binder (fly ash + alkaline) to the soil was 20% by weight was added to the treated samples during mixing. Subsequently, the treated sample was placed inside a nylon bag and exposed to a curing time of one week. The specimens are compressed within the circular enclosure of the apparatus, possessing a diameter of 70 mm and a height of 19 mm, in order to achieve a maximum dry density of 80% and the optimum amount of moisture. The test specimens were exposed to a 24-hour period of loading with different stresses, namely 25, 50, 100, 200, 400, and 800 (kPa), followed by unloading of 800, 400, 200, 100, and 50 kPa. Subsequently, various characteristics were determined.

2.3 Collapse test

This experiment involved the investigation of both treated and untreated soil samples. The samples were treated by the addition of a geopolymer solution with varying molarities, specifically (10 M, 12 M, and 14 M). In addition, the fly ash was combined with an alkaline activator at a 1:1 ratio. The binder (fly ash + alkaline) to the soil was 20% by weight was added to the treated samples during mixing. In order to facilitate the process of curing, the samples were enclosed within nylon bags for a period of one week. The specimens are compressed within the circular ring of the apparatus, having a diameter of 70 mm and a vertical height of 19 mm, in order to achieve a maximum dry density of 80% and the optimum amount of moisture. The collapse test devised by Knight in 1963 for the purpose of assessing the collapse potential (CP) of a soil specimen. The Oedometer equipment is employed in accordance with ASTM D-5333-03 [29]. The term "collapse potential" is employed to classify the level of risk associated with structural collapse. It is defined by the following equation:

$$CP\ \% = \left(\frac{\Delta H}{1+H_{\circ}}\right) * 100\% \quad (1)$$

$$CP\ \% = \left(\frac{\Delta e}{1+\Delta e}\right) * 100\% \quad (2)$$

Where:

$H_{\circ}$ = initial soil height, ΔH = the change in soil height caused by wetting.

$e_{\circ}$ = initial void ratio, Δe = variation in void ratio induced by saturation.

The degree enhancement (ID) is determined by calculating it using the following equation:

$$\text{ID}\ \% = 1 - \frac{\text{collapse potential of treated soil}}{\text{collapse potential of natural soil}} * 100$$

Table 3 presents various collapse potential values reported by ASTM D-5333 [29], these values just indicate the severity of the problem.

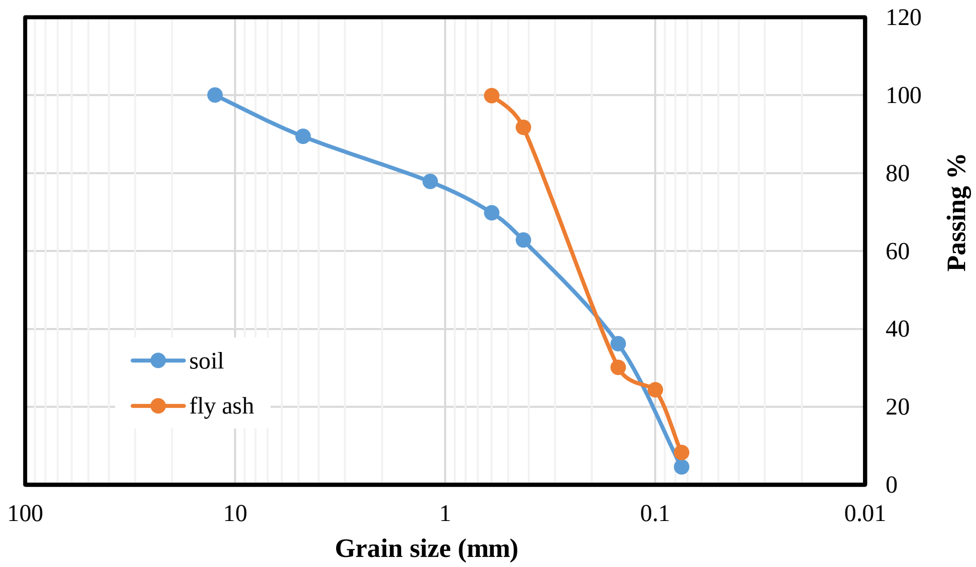


Figure 2. Grain size distribution

Table 1: Properties of soil

Soil property	Value	specification
Specific gravity	2.4	BS 1377:6B [30]
Maximum dry density (kN/m^3)	16.5	ASTM D 698 [31]
Optimum water content (%)	14%	ASTM D 698 [31]
Soil classification (USCS)	SP	ASTM D2487 [32]
Gypsum content (%)	41%	Al-Mufty and Nashat (2000) [33]

Table 2: Chemical components of soil and fly ash

Elements	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	Cr_2O_3	Mn_2O_3	Fe_2O_3	ZnO	SrO
Fly ash (wt%)	0.41	3.02	21.5	40.2	0.05	2.50	0.64	12.2	0.32	0.03	0.24	16.04	0.003	0.05
Soil (wt%)	0.76	3.74	6.15	16.26	0.21	23.05	0.15	31.33	0.30	0.04	0.05	1.61	0.01	0.41

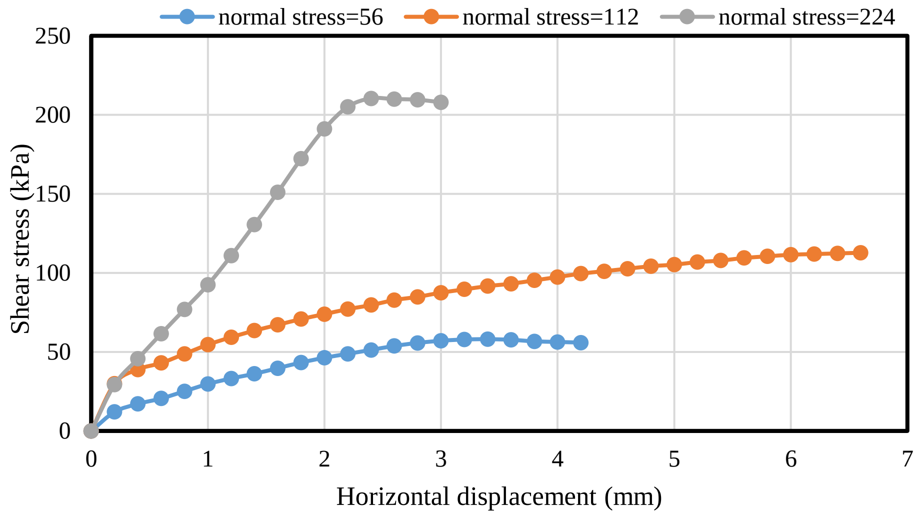
Table 3: Identification of a Collapse as Proposed by ASTM D-5333 [29]

CP %	Degree of Specimen Collapse
0	None
0.1-2	Slight
2.1-6	Moderate
6.1-10	Moderate Severe
>10	severe

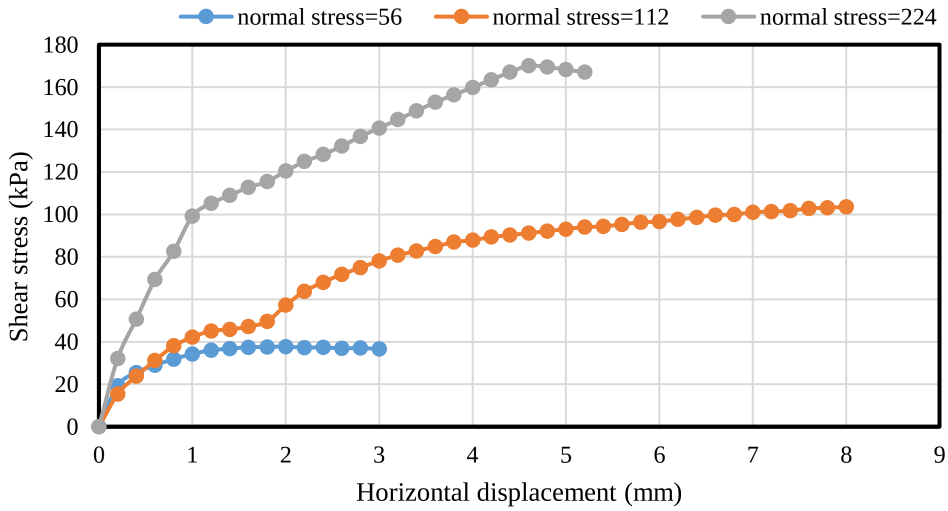
3. Results and discussion

3.1 Shear strength test

The measured shear stress-shear displacement curves for the samples were compacted to a dry density (1.65) kg/m^3 using treated and untreated gypsum soil are depicted in Figure 3. Figure 3 shows that the stress-horizontal displacement curves for the dry samples have no peak values from which the shear stress remain parallel with further displacement. The shear strength parameters for untreated and treated samples of gypseous soil are determined by a series tests of direct shear, stress & strain relationships for the soil specimens were determined by performing direct shear tests at (56,112,224) kPa normal stress, the results demonstrated an increase in the angle of internal friction (from 37 to 42 degrees), but no significant effect on cohesion for treated soil samples with geopolymer as presented in Figure 4. For geopolymer-stabilized soil, the internal friction angles were more than 50 degrees, which is one measure of strength [34], the same pattern was noticed by Correa-silva [35], and Al-Rkaby [36]. As deduced from the results, the molarity of sodium hydroxide has a significant effect on shear strength, according to Somna research 2011, the compressive strength of an alkali-activated material composed of NaOH-activated grounded fly ash increases with increasing alkali activator concentrations, with the optimal concentration at 14 M [37], Also Liang [38], and Saha [39], showed that an increasing the molality of the NaOH solution enhanced the compressive strength of geopolymers.



(a)



(b)

Figure 3. The relation between shear stress with horizontal displacement by using normal stress (56,112,224) kPa (a) natural soil (b) treated soil

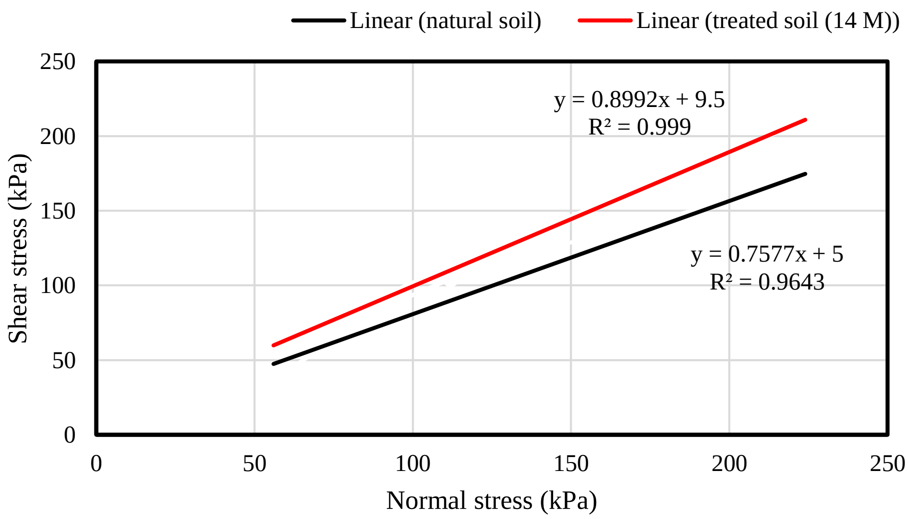


Figure 4. The shear stress-normal stress relationship of natural and 14 M geopolymer-treated soil samples

3.2 Consolidation test

The experiment is conducted using soil samples that are both in their natural state and have undergone treatment. Figure 5 explains the correlation between the void ratio and the logarithm of the effective stress. This observation demonstrates that an increase in applied pressure leads to a drop in the main consolidation rate. This discovery implies that the duration of the consolidation process increases as pressure is applied. The results demonstrate a significant reduction in void ratio, particularly under a stress level of 800 kPa. Table 4 presents a brief summary of the data. Following the implementation of geopolymer treatment on the soil, a discernible reduction in the compression index was observed. The compression index exhibited a reduction, decreasing from an initial value of 0.26000 to a final value of 0.23287 subsequent to the treatment. The swelling index and coefficient of consolidation exhibit similar trends, with a drop in values found from 0.02376 to 0.01369 and from 0.00329 to 0.00318, respectively.

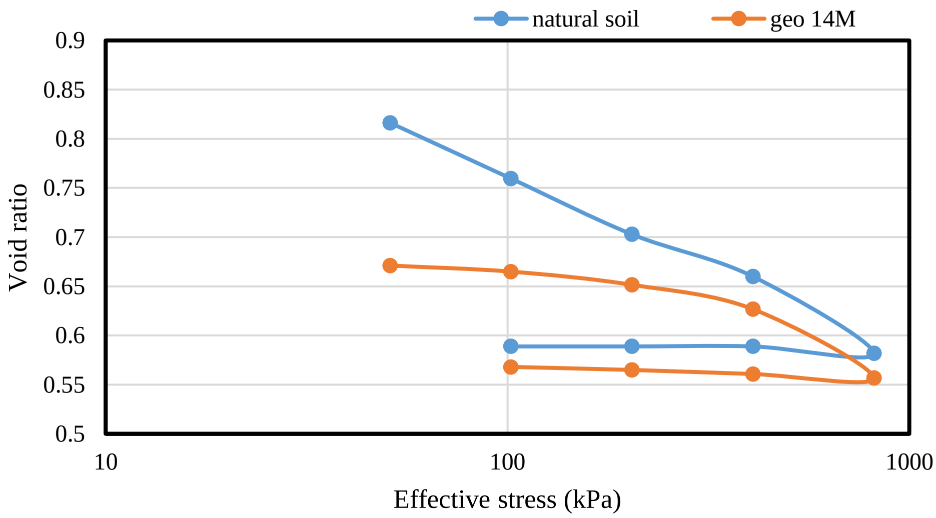


Figure 5. The logarithms of effective stress-void ratio relationship of natural and geopolymer-treated soil samples

Table 4: Compressibility characteristics of natural and 14 M geopolymer-treated soil

Compressibility characteristics	Natural soil	Treated soil (14 M)
Cc	0.26000	0.23287
Cs	0.02376	0.01369
Cv	0.00329	0.00318

3.3 Collapse test

This experiment involved the investigation of both treated and untreated soil samples. The graphical representation in Figure 6 illustrates the correlation between the logarithms of effective stress and void ratio for both treated and untreated samples. Based on the research findings, the collapse potential of the natural soil has been calculated to be 3.65, which aligns with the classification provided by ASTM D-5333 [29] as moderate. The collapse of the soil structure can be attributed to the dissolution of gypsum in water under a stress level of 200 kPa. As a consequence of the rupture of inter-particle linkages, there is an increase in the quantity of voids inside the soil. Consequently, the soil particles undergo reorganization, leading to the settling of the soil sample due to the consistent applied stress. The same observation was similarly obtained by [40], [41].

The collapse potential of soil samples treated with geopolymers exhibited variations based on the molarity of the applied geopolymer. The utilization of a geopolymer with a molarity of 10 led to a decrease in the collapse potential from 3.65% to 1.85%, resulting in a 49% improvement. Similarly, when soil samples were treated with a geopolymer of 12 molarity, the collapse potential decreased from 3.65% to 1.75%, resulting in a 52% improvement. Furthermore, the application of a geopolymer with a molarity of 14 resulted in a reduction of the collapse potential from 3.65% to 1.3%, achieving a 64% improvement Which is classified as slight.

Based on the available data, it is apparent that the application of geopolymer in soil treatment results in a decrease in the likelihood of soil collapse. The aforementioned discovery is consistent with the research conducted by [42], which similarly indicated that the utilization of geopolymer fly ash for soil stabilization led to a reduced probability of soil collapse. Furthermore, Figure 7 illustrates the correlation between the molarity of geopolymer and its potential for collapse. The data shown in the Figure demonstrates a negative correlation between the molarity of the geopolymer and the collapse potential of the soil. The aforementioned discovery indicates an increased presence of geopolymer during the process of soil stabilization results in a more efficient reduction of collapse propensity.

Geopolymer is a promising and eco-friendly method for geotechnical applications due to its capacity to increase soil stability and decrease collapse potential. Engineers and geotechnical experts may benefit greatly from this study by learning how to improve the performance of soils in a wide range of building and infrastructure projects.

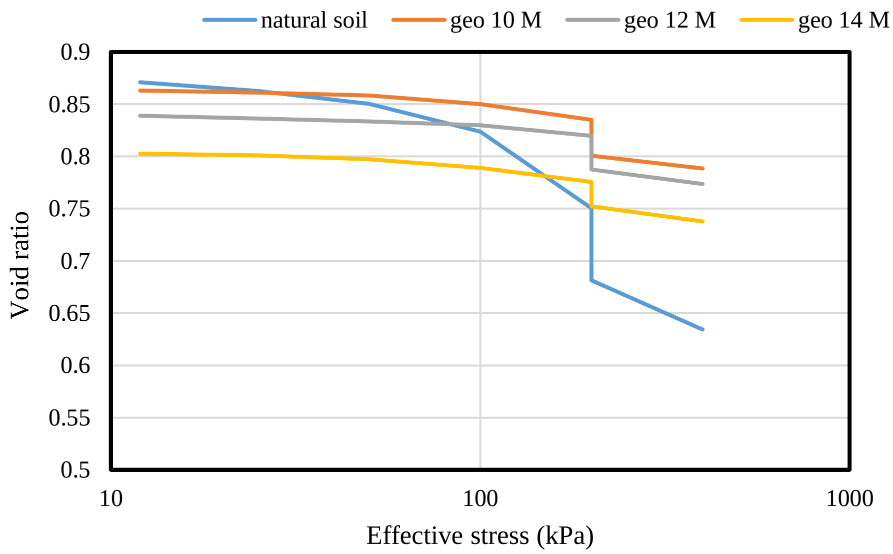


Figure 6. The logarithms of effective stress-void ratio relationship of natural and geopolymer-treated soil samples

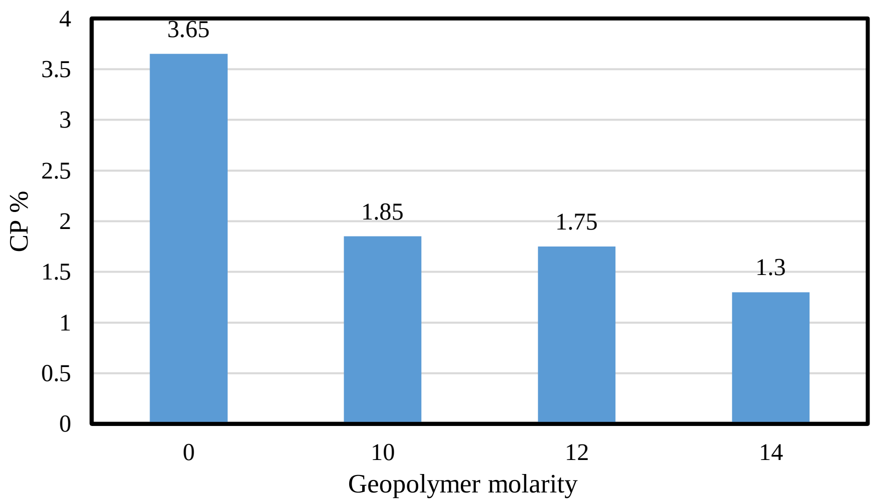


Figure 7. The effect of geopolymers molarity on the collapse potential of soil

4. Conclusion

The study's findings are summarized as follows:

1. Geopolymer-treated soil samples exhibited an increased angle of internal friction from 37 to 42 degrees, indicating improved shear strength.
2. The cohesion component of shear strength did not show a significant trend due to the effect of geopolymer.
3. The use of geopolymer treatments led to a reduction in soil compressibility.
4. The use of geopolymer treatment led to a reduction in the susceptibility of the soil to collapse, with notable decreases noted at various molarities. At a molarity of 10 M, the collapse potential showed a decrease from 3.65 to 1.85, which further decreased to 1.75 at a molarity of 12 M, and finally reached a value of 1.3 at a molarity of 14 M.
5. The best results are achieved when the sodium hydroxide concentration in the geopolymer is 14 M.

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