Environmental and Earth Sciences Research Journal
Vol. 10, No. 3, September, 2023, pp. 111-117
Journal homepage: http://iieta.org/journals/eesrj

Enhancement of Gypseous Soil Engineering Properties Through High-Density Polyethylene Polymer Addition: A Comprehensive Experimental Assessment

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https://doi.org/10.18280/eesrj.100304

Received: 24 August 2023
Revised: 31 August 2023
Accepted: 11 September 2023
Available online: 26 September 2023

Keywords:
HDPE polymer, gypseous soil, engineering characteristics, collapse potential, CBR, Tikrit region

ABSTRACT

An experimental investigation was conducted to scrutinize the influence of high-density polyethylene (HDPE) polymer on the engineering properties of gypseous soil. Soil samples, possessing 38% gypsum content, were extracted from the Tikrit region, Iraq, and were subsequently subjected to varying HDPE polymer concentrations of 1%, 3%, and 6%. An observed augmentation in the maximum dry density was noted when a minuscule quantity of 1% HDPE polymer was incorporated. However, a subsequent increase in polymer concentration resulted in a discernible decrease in dry density. Examination via the double oedometer test elucidated a significant reduction in collapse potential by 64%, 77.7%, and 83.2% upon addition of 1%, 3%, and 6% HDPE polymer, respectively. Direct shear test outcomes revealed a complex influence of HDPE polymer on soil cohesion. In the dry state, a 1% and 6% HDPE polymer addition led to a cohesion increase by 50% and 16.67%, respectively, whereas a 33.3% decrease was observed at a 3% polymer concentration. Conversely, in the soaked state, cohesion was found to decrease by 50% at 1% and 6% HDPE polymer concentrations, and entirely diminished with a 3% polymer addition. Interestingly, the internal friction angle (ϕ) exhibited an increase in both dry and soaked states with escalating HDPE polymer percentages. A contradictory behavior was noted in the California Bearing Ratio (CBR), which decreased in the dry state but increased in the soaked state with a rise in HDPE polymer ratios. In conclusion, the present study substantiates that the addition of HDPE polymer induces modifications in the engineering behavior of gypseous soil. Further research is encouraged to optimize the HDPE polymer concentration for ground enhancement applications.

1. INTRODUCTION

Gypseous soil, recognized as one of the most difficult types of unsaturated soil, poses significant challenges in the construction of infrastructure and buildings due to its unique composition. Enriched with hydrated calcium sulfate ($CaSO_4.2H_2O$), or gypsum, this soil-type exhibits distinct physical and mechanical properties that are highly sensitive to water content [1]. A prominent feature of arid and semi-arid environments, gypseous soils harbor calcium sulfate deposits that concentrate on the surface or at varying depths due to insufficient water for leaching.

Upon wetting, gypseous soils exhibit a propensity for collapse as water incites particle rearrangement when the gypsum dissolves and consequent soil volume reduction. This volumetric alteration weakens inter-particle bonds, compromising soil stability under external loads, thereby heightening the risk of structural failure. Factors influencing susceptibility to collapse encompass natural properties of the soil, geological structure, initial soil density, applied stress, and moisture content [2, 3].

Given the detrimental impact of gypseous soils on structures, soil improvement is vital. Historically, mechanical and chemical methods have been employed, with the latter two decades witnessing the exploration of cement, lime, fly ash, and other conventional materials to bolster gypseous soil engineering properties [3]. Despite their merits, these additives require substantial quantities and extended periods to exert their beneficial effects.

Recently, attention has veered towards the potential of non-traditional materials such as polymers, celebrated for their high tensile strength, pressure resistance, and exceptional soil particle adherence [4-9]. Their impressive resistance to chemicals and water further bolsters their appeal.

This research aims to elucidate the impact of varying percentages of one such polymer, High-Density Polyethylene (HDPE), on gypseous soil characteristics, including compaction parameters, collapse potential (CP), cohesion (c), internal friction angle (ϕ), and California Bearing Ratio (CBR). By enhancing our understanding of polymer-soil interactions, this study addresses a gap in geotechnical knowledge, paving the way for comprehensive future investigations.

The practical implications of this study are far-reaching. If the addition of HDPE polymer positively alters gypseous soil characteristics, it could offer an efficient and effective improvement method. Expected outcomes include enhanced soil stability and strength, reduced collapsibility, and potential incorporation of this research's findings into future construction plans in gypseous soil-rich areas.

2. MATERIALS AND LABORATORY TESTS

2.1 Materials

2.1.1 Gypseous soil

The medium gypsum content gypseous soil used in this study was gathered from Tikrit City in Salah Al-Din Governorate, Iraq. The samples were collected at a depth between 0.5 and 1 meter below the ground's natural surface. Tikrit city selection as the sampling site is the soil of this city contains a high percentage of gypsum and this soil makes a challenge to construct in this city. At the National Center for Construction Laboratories and Research Soil in Baghdad, Iraq, the physical and chemical characteristics of gypseous soil were investigated. Tables 1 and 2 show the physical and chemical properties of gypseous soil.

Table 1. Physical properties of gypseous soil

Mechanical Properties	Percentage	Standard Method
Gravel	0%	ASTM D 422
Sand	56%	
Silt	44%	
Specific gravity, Gs	2.49	ASTM D 854/02
Liquid limit (L.L) %	N.P (Non-Plastic)	ASTM D 4318 [10]
Plastic limit (P.L) %	N.P (Non-Plastic)	
D10	0.015	-------------
D30	0.027	-------------
D60	0.15	-------------
Coefficient of curvature, Cc	0.324	-------------
Coefficient of uniformity, Cu	10	-------------
maximum dry density (MDD), (kN/m^3)	16.38	ASTM D 698 Method A
optimum moisture content (%)	7%	
cohesion, c (kPa)	30(dry) 30(soaked)	ASTM D 3080
The angle of internal friction, ϕ°	35°(dry) 30°(soaked)	
collapse potential (CP) %	5.2%	ASTM D 5333
CBR %	21.6(dry) 4.3(soaked)	ASTM D 1883
Classification according to Unified Classification System (UCS)	SM	ASTM D 2487 [11]

Table 2. Chemical properties of gypseous soil

Tests	Result	Standard
Sulphate Salts (SO_3) (%)	18.081	BS 1377:3
Total Soluble Salts (T.S.S) (%)	60.786	Earth manual [12]
Gypsum Content (%)	38.032	Nashat and Al-Mufty [13]
pH value	8.31	BS 1377:3
CL (%)	0.078	BS 1377:3
Organic Matters (O.M) (%)	0.485	BS 1377:3

Note: The high values of SO_3, T.S.S, and gypsum content are indeed due to the fact that the soil is gypseous. Gypseous soil is rich in calcium sulfate, which is a type of salt. The sulfate content (SO_3) is the percentage of sulfate ions in the soil, and the total dissolved salts (TSS) is the total amount of dissolved salts in the soil. Gypsum content is the percentage of calcium sulfate in the soil.

2.1.2 High-density polyethylene (HDPE)

Polyethylene is a simple polymer made up of -CH2- units that are repeated. It is produced by the addition polymerization of ethylene with the formula (CH2=CH2). The properties of polyethylene depend on how the ethylene is polymerized. For example, when ethylene is polymerized in the presence of organometallic compounds at moderate pressure, the product is high-density polyethylene (HDPE). HDPE has a high molecular weight and is therefore strong and rigid. According to its chemical composition, polyethylene belongs to a type of polymers that are referred to as organic polymers. The basic polymer repeat unit has four hydrogen atoms and two carbon atoms. One of the characteristics of polyethylene is its high degree of durability, softness, lightness, ease of manufacturing, low water absorption, inert chemical nature (i.e., insoluble in any solvent at room temperature), good resistance to acids as well as bases, and low degree of glass transition (-120°C), because of this, in addition to its electrical properties, it is flexible and highly resistant to moisture [8, 14]. The physical and chemical properties of HDPE polymer are shown in Tables 3 and 4, respectively.

Table 3. Physical properties of HDPE polymer

Chemical Formula	$(C_2H_4)_n$
Appearance (Form)	Powder
Color	White
Solubility	Dissolved in (xylene or toluene) dissolvent, insoluble in water
Density (g/cm^3)	0.960
Flow Index (at 190°C), $g\ (10\ min)^{-1}$	1.5
Tensile Strength (psi)	4300

Table 4. Chemical composition* of HDPE polymer

Element	Content %
Carbon	99.31

*The test is conducted in the College of Science, physical laboratory at Al-Nahrain University.

2.2 Laboratory tests

The tests used in this research (compaction test, double oedometer test, direct shear test, and CBR test). These tests were chosen because they are standard tests used to evaluate the engineering characteristics of soil. They have been used in many previous studies and are well-established methods for measuring the characteristics of gypseous soil.

The choice of HDPE polymer percentages of 1%, 3%, and 6% in soil improvement projects is often based on empirical studies, field trials, and engineering judgment rather than the scientific rule. 1% of HDPE Polymer: A low percentage is often used for initial trials and can provide a subtle improvement in soil characteristics without dramatically altering its characteristics, Useful for evaluating the potential benefits of polymer treatment before committing to higher percentages. 3% of HDPE polymer: A moderate percentage that can lead to noticeable soil improvements and achieves a balance between effectiveness and cost. 6% of HDPE polymer: This can lead to significant changes in soil characteristics.

Useful for addressing challenging soil conditions, but cost considerations may come into play.

2.2.1 Compaction test

Using the standard proctor compaction test in accordance with ASTM D 698 Method A [15], the compaction tests of the untreated gypseous soil and treated gypseous soil with different percentages of 1%, 3%, and 6% of high-density polyethylene (HDPE) polymer were conducted. It was made with a mold that was 16.5 cm in height and 10 cm in diameter. To determine the maximum dry density and optimum moisture content, the gypseous soil samples were compacted in three layers with 25 blows on each layer using a 2.5 kg hammer that was dropped from a height of 30.5 cm. The test was conducted on both untreated and treated gypseous soils.

2.2.2 Collapse test

In accordance with ASTM D 5333 [16], collapse tests have been conducted with an oedometer device. The collapse potential (CP) of untreated gypseous soil and treated gypseous soil with different percentages of high-density polyethylene (HDPE) was determined using a double oedometer test. The collapsible potential (CP) is calculated at a stress of 200 kPa and according to the following formula:

$$CP = \frac{e1-e2}{1+e0} \times 100\ \% \quad (1)$$

where,

e1: the void ratio at the required stress level before soaking (dry).

e2: the void ratio at the required stress level after soaking.

e0: the initial void ratio.

The collapse potential is expressed as a percentage, and a higher percentage indicates a higher risk of collapse.

Table 5 shows the severity in relation to the collapse potential (CP) from Pells et al. [17].

Table 5. Collapse identification

Severity	Collapse Potential (CP) %
No problem	0-1
Moderate	1-5
Trouble	5-10
Severe	10-20
Very severe	20<

2.2.3 Direct shear test

Direct shear tests were conducted to determine the shear strength parameters (c, ϕ) of untreated and treated gypseous soil with different percentages of high-density polyethylene (HDPE). The tests were conducted in accordance with ASTM D 3080's recommended method [18] for samples in dry and soaked states. The specimen size was (60×60×20) mm. The specimens were compacted to their maximum dry density. The specimens were subjected to normal stresses (chosen based on preliminary tests): 100, 200, and 400 kN/m^2, then sheared along a horizontal plane in direct shear apparatus.

2.2.4 California Bearing Ratio (CBR) test

According to ASTM D1883 [19], the CBR test was performed on both untreated and treated gypseous soil. The CBR test measures a material's resistance to being penetrated by a standard plunger under controlled moisture and density conditions. The California Division of Highways developed it as a method for identifying and evaluating the relative quality of subgrade, sub base, and base soils for road pavements and below some of the structure's foundations. The California Bearing Ratio (CBR) is a measure of the strength of a soil or pavement material. It is calculated by dividing the load required to penetrate the material by a standard load and expressing the result as a percentage. CBR values are typically used in the design of flexible pavements, as they provide an estimate of the material's ability to support traffic loads. The CBR mold used in this study has a 15.2 cm diameter and 17.8 cm height with a cellar, compaction hammer (2.5kg), and surcharge weights (4.5kg). A compression machine equipped with a CBR penetration piston (4.953 cm diam.) with a cross-sectional area of 19.4 cm2 and capable of a penetration rate of 1.28 mm/min. The specific conditions under which a CBR test is performed (such as moisture content, compaction level, and penetration rate) are important to ensure that test results accurately reflect real-world soil behavior. The penetration rate is one such important condition. The penetration rate of 1.28 mm/min is standardized because it has been found to be a rate that is slow enough to allow the soil to deform, but not so slow that the test takes an excessive amount of time.

3. PHYSICAL AND ENGINEERING CHARACTERISTICS OF GYPSEOUS SOIL

The engineering characteristics of the soil that has to be treated (gypseous soil) have been determined by physical tests in the lab; the results are shown in Table 1. In accordance with ASTM D854/02, the soil's specific gravity is calculated [20], however, because gypsum dissolves in water, Kerosene was used instead of water [21]. Grain size distribution testing was performed on the soil in accordance with ASTM D422 [22] to classify the soil. Figure 1 Shows that the soil can be classified as silty sand (SM) according to the Unified Soil Classification System (USCS) [23].

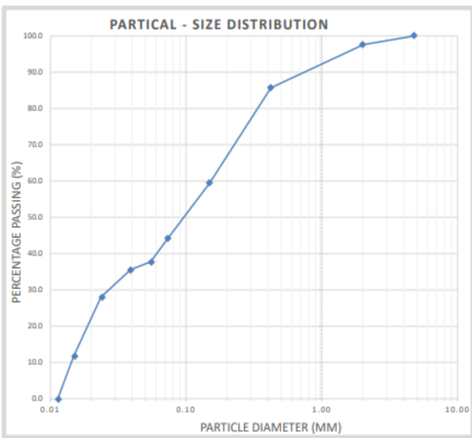

Figure 1. Grain size distributions of gypseous soil

3.1 Chemical tests and EDX test

The chemical tests [12, 13, 23] and EDX (Energy Dispersive X-Ray Spectroscopy) test were conducted on gypseous soil samples as shown in Tables 2 and 6. The chemical test was conducted at the National Center for Constriction Laboratories and Research Soil in Baghdad, while the EDX test was conducted in the College of Science, the Physics Laboratory at Al-Nahrain University. The gypsum content is determined according to Nashat and Al-Mufty's method (Hydration method) [13], this method recommends drying the soil sample in an oven at 45℃ until the weight of the sample becomes constant. The weight of the sample was recorded at a temperature of 45℃. Then, the same sample drying in an oven at a temperature of 110℃ until the weight of the sample became constant. The weight of the sample was recorded at a temperature of 110℃. The gypsum content was determined according to the equation:

$$X\% = \frac{(W45℃ - W110℃) \times 4.778}{W45℃} \times 100\% \quad (2)$$

where,

X = Gypsum content (%).

W45℃ = Weight of soil sample at (45℃).

W110℃ = Weight of soil sample at (110℃).

Table 6. The results of the EDX test of gypseous soil

Element	Wt. (%)	Wt. (%) Sigma
Antimony (Sb)	44.14	1.50
Sulfur (S)	15.36	0.69
Calcium (Ca)	15.05	0.56
Silicon (Si)	10.11	0.58
Carbon (C)	5.75	2.43
Aluminium (Al)	4.19	0.32
Oxygen (O)	1.94	0.96
Magnesium (Mg)	1.92	0.21
Iron (Fe)	1.54	0.13

4. RESULTS AND DISCUSSION

4.1 Compaction test

Figure 2 and Table 7 below show the compaction test results and provide a number of conclusions, as seen within the following:

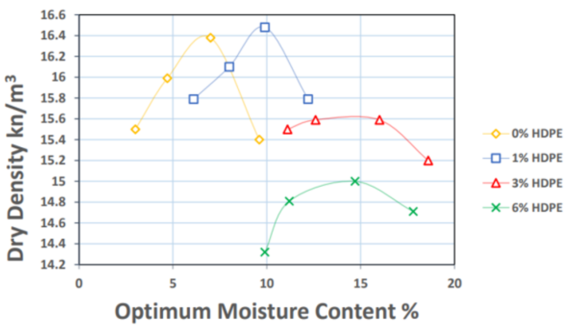

Figure 2. Results of the compaction test on untreated and treated gypseous soil by HDPE polymer

1. The maximum dry density of the treated soil was increased by about 0.67% at 1% of HDPE polymer, and then when the additives with this polymer were increased to 3%, the maximum dry density decreased by about 4.6% and decreased by about 8.4% at 6% of HDPE polymer.
2. The optimum moisture content increased about 45% at 1% of HDPE polymer, increased about 108.6% at 3% and increased about 110% at 6% of HDPE polymer, and it seemed to remain steady in these percentages 3% and 6% of HDPE polymer.

Table 7. The results of the compaction test on untreated and treated gypseous soil by HDPE polymer

Materials	Maximum Dry Density (kN/m³)	Optimum Moisture Content (%)
Gypseous Soil	16.38	7
Gypseous Soil + 1% HDPE	16.49	10.2
Gypseous Soil + 3% HDPE	15.62	14.6
Gypseous Soil + 6% HDPE	15	14.7

4.2 Collapse test

The untreated soil sample that was used in this test has a moderate gypsum content 38%, was compacted to a maximum dry density of 16.38 kN/m³, and 7% optimum water content. The result of the collapse potential was 5.2%, according to Pells et al. [17], which was recognized as a trouble degree of collapse. Depending on the amount of improved materials, the addition of HDPE polymer reduced the collapse potential. Figure 3 shows the effect of HDPE polymer increasing on collapse potential.

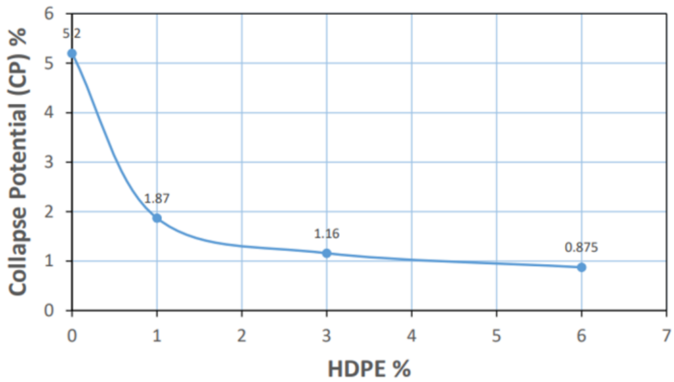

Figure 3. Effect of HDPE polymer increasing on collapse potential

Gypsum dissolution, soil particle reorientation, and the breakdown of the cementation between soil particles are all factors that contribute to the collapse potential of gypseous soil [9]. The collapse potential decreasing about 64% at 1% of HDPE polymer and it was 1.87%. The collapse potential decreasing about 77.7% at 3% of HDPE polymer and it was 1.16%, while it decreasing about 83.2% at 6% of HDPE polymer, and it was 0.875%. Table 8 shows the results of the double oedometer test.

Table 8. The results of the double oedometer test (DOT) on untreated and treated gypseous soil by HDPE polymer

Materials	Collapse Potential (%)	Decreasing in Collapse Potential (%)
Gypseous Soil	5.2	--------
Gypseous Soil + 1% HDPE	1.87	64
Gypseous Soil + 3% HDPE	1.16	77.7
Gypseous Soil + 6% HDPE	0.875	83.2

4.3 Direct shear test

For the dry state, the cohesion increased by about 50% by adding 1% of HDPE polymer, decreased by about 33.3% by adding 3% of HDPE polymer, and increased by about 16.67% by adding 6% of HDPE polymer to the gypseous soil sample dry weight. For the soaked state (the untreated and treated soil samples were soaked in water for 24 hours), the cohesion decreased by about 50% by adding 1% of HDPE polymer, decreased about 100% by adding 3% of HDPE polymer, and decreased about 50% by adding 6% of HDPE polymer to the dry weight of gypseous soil sample. Figure 4 shows the effect of HDPE polymer increasing on the cohesion of gypseous soil.

And for internal friction angle (ϕ) in the dry state was no change at adding 1% of HDPE polymer and it was increased about 22.9% by adding 3% of HDPE polymer and it increased about 5.7% by adding 6% of HDPE polymer to dry weight of gypseous soil sample. Internal friction angle (ϕ) in the soaked state was increased about 6.67% by adding 1% of HDPE polymer, increased about 30% by adding 3% of HDPE polymer, and increased about 20% by adding 6% of HDPE polymer to dry weight of gypseous soil sample. Figure 5 shows the effect of HDPE polymer increasing on the internal friction angle (ϕ) of gypseous soil.

4.4 California Bearing Ratio (CBR) test (the results)

To prepare the soil sample for the CBR test, it was weighed approximately 4.5kg. After that, different percentages of HDPE polymer were mixed with the dry soil at the optimum moisture content until the mixture was homogenized. The gypseous soil samples were compacted in three layers, with 56 blows applied on each layer (Compact soil according to ASTM D698). The hammer used for compaction weighed 2.5 kg at a free fall. Surcharge weights (4.5kg) were put on the last layer. For the soaked state, the mold was placed in water for 96 hours and then put in the CBR machine. In order to make contact with the soil surface, the penetration plunger was placed in the middle of the compacted soil sample and must touch the soil surface. The CBR test was conducted by applying the load through the penetration readings of (0.0, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, and 7.5 mm).

In the dry state, the CBR of the untreated gypseous soil was 21.5%. The CBR values decreased when the HDPE polymer percentage was increased, by adding 1% of HDPE the CBR value was 17.14%. By adding 3% of HDPE polymer to the dry weight of the gypseous soil sample the CBR value was 8.7% and by adding 6% of HDPE polymer the CBR value was 9.4%, as shown in Figure 6.

And in the soaked state, the CBR of the untreated gypseous soil was 4.3%. the CBR ratio increased when the HDPE polymer percentage was increased, by adding 1% of HDPE the CBR value was 4.5%. By adding 3% of HDPE polymer to the dry weight of the gypseous soil sample the CBR value was 6.7% and by adding 6% of HDPE polymer the CBR value was 10.7%, as shown in Figure 6. The effect of adding HDPE polymer on CBR ratio.

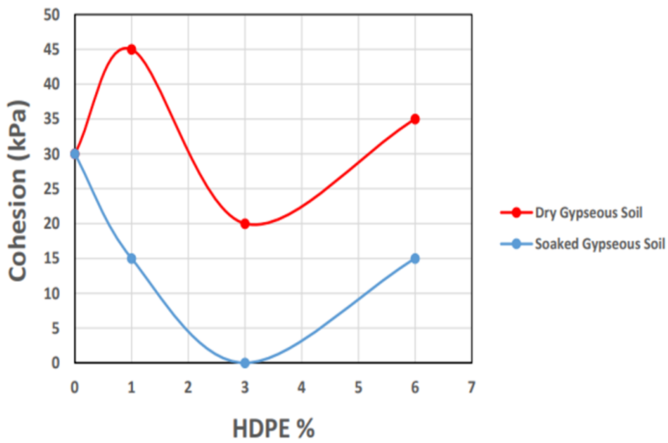

Figure 4. Effect of HDPE polymer increasing on the cohesion of gypseous soil

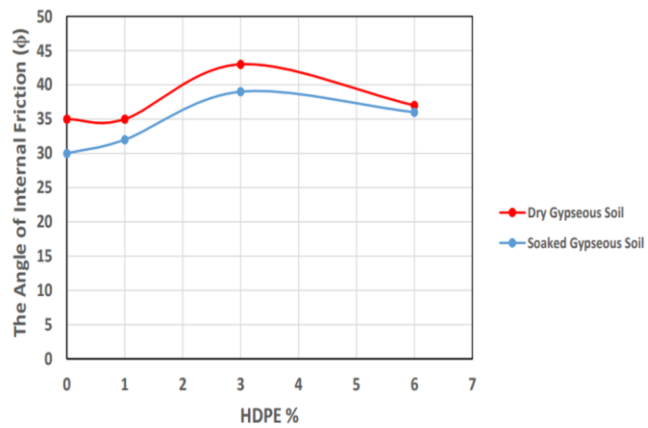

Figure 5. Effect of HDPE polymer increasing on the internal friction angle (ϕ) of gypseous soil

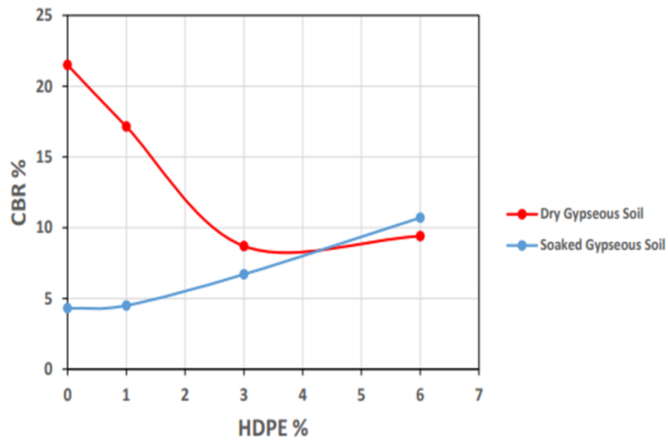

Figure 6. The effect of adding HDPE polymer on CBR

5. CONCLUSIONS

The maximum dry density increased from 16.38 kN/m^3 for the gypseous soil to 16.49 kN/m^3 for the soil mixed with 1%

of HDPE polymer. However, as the percentage of HDPE polymer increased to 3% and 6%, the maximum dry density decreased to 15.62 kN/m^3 and 15 kN/m^3, respectively.

The maximum dry density of gypseous soil is increased by the addition of HDPE polymer up to 1%. This is because the polymer molecules bond to the soil particles, causing them to aggregate and pack more tightly together. However, when the amount of polymer is increased beyond 1%, the polymer molecules start to tangle and form a network that prevents the soil particles from packing as tightly. This is why the maximum dry density decreases with increasing polymer content.

The collapse potential of the gypseous soil was measured at 5.2%. However, when 1% of HDPE polymer was added, the collapse potential decreased to 1.87%, indicating a significant reduction of 64% compared to the original soil. Furthermore, as the percentage of HDPE polymer increased to 3% and 6%, the collapse potential decreased to 1.16% and 0.875%, respectively. This represents a substantial decrease of 77.7% and 83.2% in collapse potential compared to the untreated gypseous soil. The addition of HDPE polymer to gypseous soil can reduce its collapse potential by several mechanisms: The HDPE polymer molecules can coat the surface of the gypsum crystals, preventing them from dissolving. The HDPE polymer molecules can fill in the voids between the soil particles, making it more difficult for water to enter the soil and The HDPE polymer molecules can form a network of bonds between the soil particles, making the soil more cohesive.

In the dry state, adding 1% of HDPE polymer resulted in a 50% increase in cohesion, while adding 3% of HDPE led to a significant decrease of 33.3% in cohesion, and adding 6% of HDPE polymer increased the cohesion by 16.67%, compared to the untreated gypseous soil.

This is because the HDPE polymer filled in the voids between the soil particles and created a stronger bond. However, the cohesion decreased when the amount of HDPE polymer was increased to 3% or 6%. This is because the HDPE polymer started to coat the surface of the soil particles and prevent them from bonding together.

In the soaked state, the addition of HDPE polymer caused a decrease in cohesion. Adding 1% of HDPE polymer resulted in a 50% decrease in cohesion, and adding 3% and 6% of HDPE polymer led to decreases of 100% and 50% in cohesion, respectively, compared to the untreated gypseous soil. This is because the water molecules in the soil were able to displace the HDPE polymer and reduce the cohesive force.

The internal friction angle (ϕ) of the gypseous soil showed an increase with the addition of HDPE polymer in both the dry and soaked states. In the dry state, the internal friction angle was not changed by adding 1% of HDPE polymer, while it was increased about 22.9% by adding 3% of HDPE polymer, and increased about 5.7% by adding 6% of HDPE polymer. the internal friction angle of the gypseous soil sample did not change when 1% of HDPE polymer was added in the dried state. This is because the amount of HDPE polymer was not enough to significantly affect the properties of the soil. However, when 3% or 6% of HDPE polymer was added, the internal friction angle increased significantly. This is because the higher percentages of HDPE polymer were able to more effectively adhere to the soil particles and fill in the voids between the particles.

In the soaked state, the internal friction angle increased by 6.67% with 1% of HDPE polymer, increased by 30% with 3% of HDPE polymer, and increased by 20% with 6% of HDPE polymer. the internal friction angle of the gypseous soil sample increased even more with the addition of HDPE polymer. This is because the water molecules in the soil helped to disperse the HDPE polymer molecules, allowing them to more evenly coat the soil particles. As a result, the cohesiveness and strength of the soil were further increased.

Overall, the addition of HDPE polymer can be an effective way to increase the internal friction angle of gypseous soil. This can improve the stability of the soil and make it less susceptible to erosion and landslides.

In the dry state, the CBR of the untreated gypseous soil was 21.5%. However, upon adding HDPE polymer, the CBR decreased. Adding 1% of HDPE polymer resulted in a decrease of approximately 20.3% in CBR, while adding 3% and 6% HDPE polymer led to significant decreases of 59.5% and 56.3%, respectively, compared to the untreated gypseous soil. This is because HDPE polymer has a lubricating effect on the soil particles. The polymer molecules can slide between the soil particles, making it easier for them to shear. This results in a decrease in the bearing capacity of the soil.

In contrast, in the soaked state, the CBR of the untreated gypseous soil was 4.3%. The CBR exhibited an increase with higher HDPE polymer ratios. Adding 1% of HDPE polymer led to a CBR increase of approximately 4.7%, while adding 3% and 6% of HDPE polymer resulted in significant increases of 55.8% and 148.8%, respectively, compared to the CBR of untreated gypseous soil in a soaked state. This is because HDPE polymer is a synthetic polymer that is known to improve the strength and stiffness of soil. The polymer molecules bind to the soil particles, making them more cohesive and less likely to deform under load.

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NOMENCLATURE

HDPE	high-density polyethylene
ASTM	American Society for Testing and Materials
CBR	California Bearing Ratio
Gs	specific gravity of soil solids
MDD	maximum dry density
OMC	optimum moisture content
Cc	Coefficient of curvature
Cu	Coefficient of uniformity
O.M	Organic Matters
CP	collapse potential
CL	Chlorides
c	cohesion
kPa	kilopascal
Psi	Pound per square inch
DOT	double oedometer test
N.P	Non-Plastic