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Influence of Initial Saturation Level on Collapsibility of Polymer-Treated Gypsum Soils

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ABSTRACT

During the current study, several single odometer tests were executed to explore the exert an influence of initial saturation levels on the collapsibility of both natural and polymer-treated gypseous soil. Two gypseous soils with different gypsum concentrations (18 and 58%) were taken from various locations within the Salah-Al-Deen government in Iraq. Many studies have examined the influence of polymer content on the shear strength, collapsibility, and permeability of gypseous soil. This study aims to ascertain how polymer-treated compacted gypseous soils at field dry unit weight are influenced by the initial saturation ratio considering their collapsibility. Soils were compacted with different initial water content to specify different initial saturation levels from 20 to 90% for each case. Polymer was added to soils with three percent (3, 6, and 9%). The stabilizer concentration of the polymer was previously diluted in water added to the soil mixture. Depending on the moisture content, the dilution ratio was specified to achieve a certain saturation degree and the amount of stabilizer used. The results show that the collapse index sharply dropped as the beginning saturation ratio increased. The optimum initial saturation level that achieves minimum collapse index is 50% for natural and polymer-treated soil. The optimum polymer content that achieved the minimum collapse index was 3%. The soil was compacted at an initial saturation level of 50% and polymer content of 3%, decreasing the collapse index for soil with gypsum content of 18% and 58% by 92% and 89%, respectively. A theoretical equation (which yielded an R2 value of 0.925) was predicted to calculate the potential collapse index of natural and polymer-treated gypseous soils that incorporates all the coefficients studied during this research.

1. INTRODUCTION

When exposed to atypically high moisture levels, many soils worldwide undergo substantial settlement or collapse. A broad range of problematic soils includes collapsible gypseous soil. Areas that are dry or semi-arid are home to gypseous ground. In this place, as in Iraq, gypsum deposits are typical. Any form of unsaturated soil that exhibits a dramatic reorganization of particles in soil subjected to a significant volume change is called gypseous ground. Structures or dams constructed on gypseous soil are susceptible to unexpected deformations that may result in catastrophic failure. Some structures in Iraq claim to exhibit distinct fissure patterns and unusual deformations, primarily due to the interaction between water and the gypseous soils that support them. It is well known that gypseous soils exhibit rapid collapsible behavior when exposed to water despite having a high load capacity and low compressibility when dry. When gypseous soil comes into direct touch with water, it can collapse. The disintegration of various salts within gypseous soil mass will create new pore spaces within the soil matrix and disintegrate the binding connections that bind the particles. The mineral gypsum, calcium sulfate ($CaSO_4.2H_2O$), is hydrated and has 2.6 g/l at 25℃ intermediate solubility. Gypsum plays the role of cement in the soil structure when it is dry. It doesn't prove easy to characterize the characteristics of unsaturated soil containing gypsum in many geotechnical engineering applications [1-3].

To mitigate the structural damage, it is necessary to enhance the gypseous soil using mechanical and chemical means. The mechanical approach involves physically removing and/or adding soil. The chemical approach is generated by adding an item that can change the fundamental characteristics of soil through chemical interactions [4].

Numerous researchers have evaluated the performance of these soils and suggested different additions. An assortment of methodologies, such as stabilization by chemical additives, can enhance the geotechnical properties of gypsum soils without causing harm from gypsum failure. Among these substances are iron fillings, calcium carbonate, barium chloride, silica fume, cement, and lime [5].

Non-traditional suburban materials, including polymers and resins, which are noted for their efficiency in only a brief period, are now required to meet the expectations of the economy and the environment. Still, there is a dearth of information regarding unconventional suburban materials, particularly polymers. Instead of concentrating on performance mode, the researchers sought enhancements because the firms, for financial reasons, do not know the chemical makeup of the polymer. Research on the effects of polymers and resins—not previously used extensively—on gypseous soil engineering properties has become increasingly relevant [4].

Conventional bituminous compounds, fly ash, lime cement, and other sandy soil stabilizers require prolonged curing. Therefore, polymer stabilizers are increasingly used due to their consistent chemical characteristics and rapid curing durations. Bituminous materials, fly ash, cement, and lime are the main ingredients in traditional soil stabilization. Numerous unconventional materials, such as tree resin emulsions, enzymes, acids, and polymer emulsions, are available for soil stabilization as scientists and researchers continue to develop new engineering materials. The following are the benefits these stabilizers offer over conventional stabilizers [6].

a) Steady-state chemical features.
b) They generate lowered swelling and heaving.
c) Reduce the amount of pollution that is produced.
d) They preserve resources from nature.

Numerous studies have examined the impact of polymers on the characteristics of gypseous soils. In the study by Zandieh and Yasrobi [6], the mechanical properties of polymer-stabilized soil were assessed using a simple test. Three distinct types of in-development polymer stabilizers were compared to a product ready for the market. The findings demonstrate that adding polymer additives significantly increases the strength of stabilized sandy soil in dry and wet situations. After reading about the technique, it was simpler to determine the relative advantages and disadvantages of each product.

Two distinct polymer types were studied by Xing et al. [7] at various doses. The key results show that these polymers increase the compressive strength of the improved sample from 0.03 N/mm^2 to 5.2 N/mm^2 for the control sample. Dune sands made of various polymers cure best after seven days. Furthermore, during the first 24 hours of the curing process, the UC strength of stabilized samples improves with temperature and declines with an increase in salt concentration from 1 to 10 percent.

In the study by Najah et al. [8], it investigated how additional polymers affected the characteristics of several soil types. Tests in the lab were carried out after adding polymer in different proportions of 5, 2.5, and 1.25% from soil dry weight. At 5% polymer content, the ML soil's maximum dry density increased, whereas the SP and SM soil’s maximum dry density declined as the polymer percentage increased. Furthermore, it was shown that the soils' plastic and liquid limits rose as the polymer content increased. In conclusion, the strength (14-day curing period) of the Gypseous soil was found to rise at 1.25 percent polymer content and 5% for the ML soil but to decrease at 5% for the SM soil.

By employing soil with a 36% gypsum concentration and combining it with 9%, 6%, and 3% Novolac polymer and copolymer, Mohammed et al. [4] enhanced the compaction properties, collapsibility, and permeability. Concerning the untreated soil, the results from experimental work demonstrated discernible enhancement in the soil's permeability and collapsibility when adding polymer components. Furthermore, the most significant improvement in collapsibility was noticed by adding polymer materials (novolac polymer and copolymer) with 3%, which attained 44.5 and 46%, respectively, in 3 hours. In just one day, the permeability of the copolymer improved by 98.6% and that of the novolac polymer by 86.2%.

To enhance the gypseous soil's engineering qualities, Ahmed et al. [9] utilized a 36% gypsum concentration soil from a single area southwest of Baghdad, almost 100 kilometers (62 mi). The soil was then blended with (9%, 6%, 3%) copolymer and styrene-butadiene rubber. In contrast to untreated soil, the experimental work's results enhance the soil's bearing capacity, permeability, and collapsibility when treated with styrene-butadiene rubber and copolymer.

The technical properties of gypseous soil infused with xanthan gum biopolymer have been researched by Theyab et al. [10]. Gypseous soils have been blended with varying proportions of 6, 4, and 2 xanthan gum. According to the compaction data, xanthan gum lowers the maximum dry density and raises the ideal water content. The medicated gypseous soils with xanthan gum showed a minimal collapse potential between (30-45%). Substantial shear strength advancements were observed in the direct shear results of soils treated with biopolymer. The current study's findings suggest that xanthan gum biopolymer enhancement is an eco-friendly way to enhance gypseous soil's engineering qualities.

Samples of soil from the west of Karbala, which contained 36% gypsum, were studied by Mohammed et al. [11]. The study involved adding several amounts of novolac polymer (9%, 6%, and 3%) and contrasting the results with samples similarly treated with cement in equivalent proportions. The three engineering properties being addressed are collapsibility, shear strength, and permeability. Based on the findings, 3% of weight added per weight of novolac increased collapsibility to 57.8, while adding 6% weight per weight of novolac increased permeability to 86.2% and bearing capacity to 25.2%, respectively.

Casein biopolymer was employed by Theyab et al. [12] as a novel binder to improve gypseous soil and reduce milk waste. Casein raises the ideal proportion of moisture and reduces the maximum dry density, according to the compactor results. The soil collapse potential treated with casein was 65–80% less than untreated soil. Both under wet and dry conditions, the casein-treated soil's shear strength was greatly enhanced. The study's findings point to recycled casein as a more environmentally friendly gypseous soil treatment ingredient than conventional chemicals.

To create a soil combination, pectin was utilized as a streamlined biopolymer in Hussein et al. [13] and applied in three separate concentrations (2, 1, and 0.5%). In addition, four different gypsum contents (62, 40, 20, and 10%) were added to the mixture to assess its characteristics by developing an engineering model. The results demonstrated a considerable drop in calcium hardness and collapsed potential values because of the bio gel's pore-filling capabilities and ability to encapsulate soil particles. For soils 1, 2, 3, and 4, the percentage decline in calcium hardness values is 0.67, 73, 75, and 68%, respectively. Collapse potential values fell in percentage terms (0.63, 0.63, 0.65, and 0.7%) following soils 1, 2, 3, and 4.

By regularly varying the wetness and drying conditions, Muhauwiss et al. [14] examined the resilience and potency of gypseous soil enhanced by pectin biopolymer. Following a series of drying and wetting cycles (1, 5, 10, and 15), soil containing 40% gypsum was combined with 2% pectin biopolymer. The findings demonstrate that the shear strength of the pectin biopolymer-treated gypseous soil raised more with periodic wetting and drying until cycle 5. Following this, the strength of the soil gradually decreased until cycle 15, owing to incomplete re-formation during re-drying and dissociation of pectin monomers under hydration. The force decreased by roughly 22% until ten cycles. Some strength and strength restoration were evident even after multiple cycles.

The collapsibility of gypseous soil that has been treated with polymers and left untreated will be explored in the present investigation with regard to different initial moisture levels. Many studies in the past studied the impact of the polymer content on the collapsibility, permeability, and shear strength of the gypseous soil. When compacting the soil at the field's unit weight, it is necessary to specify the optimum moisture content for compaction, which gives the best bonding between the treated soil particles and reduces the possibility of collapse as much as possible. Therefore, this study aims to ascertain how compacted polymer-treated gypseous soils at the field's dry unit weight affect collapsibility by the initial saturation ratio. It would also be anticipated that a mathematical formula could duplicate the compressibility of gypseous soil, both naturally occurring and treated with polymers.

2. THE EXPERIMENTAL AND USED MATERIAL PROGRAM

2.1 Gypseous soils

For this investigation, two gypseous soils with different gypsum concentrations were taken from various locations within the Salah-Al-Deen government in Iraq. Approximately 13.7 kilometers north of Tikrit city, the first gypsum- soil (58% gypsum) was extracted from Tikrit University. The second soil is from Bijy City, 53 km north of Tikrit City, with 18% gypsum content. Samples were collected between 1 and 1.5 meters below the surface of the natural earth. The undisturbed earth sample was air-dried, homogenized, bagged in sealed bags of plastic, and sent to the Soil Mechanics Laboratory at the Civil Engineering Department, College of Engineering, Tikrit University, to assess the soil's engineering properties. The gypsum content is determined according to the study by Snodi and Hussein [15]. The used soil's grain size distribution is demonstrated in Figure 1. The chemical and physical properties are presented in Table 1.

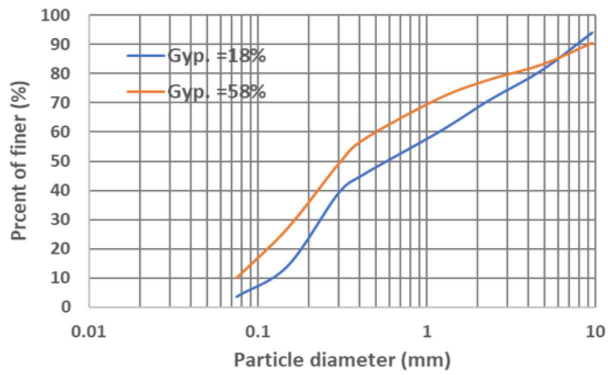

Figure 1. Utilized the size distribution of soil fragments

2.2 Polymer

Long hydrocarbon chains make up the big molecules known as polymers. Because they are easily manipulated, one can create materials with a wide range of properties by combining polymers in theoretically limitless combinations. As a result, polymers are employed in several sectors. For soil stabilization, a range of polymers, including cationic, anionic, and non-ionic polymers, were suggested [16].

The polymerization strategy of aqueous polymers can be described by three processes: pore filling, physicochemical reaction, and enwrapping. Applying polymer solutions to soil causes part of the matter to melt on the outermost layer of aggregate and fill in the spaces left by the particles. When the groups that are hydrophilic (-OOCCH3) in the polymer molecule's molecular arrangement interact chemically with the ions that are attracted of soil particles, the soil that was stabilized and the polymer molecule form physicochemical bonds. Long chain polymer macromolecules enclose the aggregate surfaces through these linkages, and they entwine around them resulting in elastic and viscoelastic barriers that constrain the soil's ability to inflate and collapse [17, 18]. Table 2 shows the properties of the polymer used.

Table1. The utilized soil properties

Properties	Soil-1	Soil-2	Detail Specifications
Gypsum Content, (%)	18	58	
Natural Water Content, (%)	4.47	5.36	ASTM D-2216
Liquid Limit (L.L)	N.L	N.L	ASTM D-4318
Plastic Limit (P.L)	N.P	N.P	ASTM D-4318
Specific Gravity Gs	2.52	2.38	ASTM D-54
Friction angle, φ, (º)	34.8	36.9	ASTM D-3080
Cohesion c, (kPa)	14.4	17.2	ASTM D-3080
D_{10} (mm)	0.123	0.077	
D_{30} (mm)	0.247	0.173	
D_{60} (mm)	1.16	0.558	
Classification (USCS)	SP	SP-SM	ASTM D-2487
Maximum dry unit weight (kN/m^3)	17.4	15.5	ASTM D-698
Minimum dry unit weight (kN/m^3)	12.1	11.3	ASTM D-4254
Field dry unit weight (kN/m^3)	15.9	14.35	ASTM D-4531
Coefficient of uniformity (Cu)	9.76	7.47	ASTM D-4254
Coefficient of curvature (Cc)	0.43	0.70	ASTM D-4254
Ph-value	8.1	7.84	
Total sulphate content (SO_3), (%)	25.4	64.6	

Table 2. Details of the utilized polymer

Property	Values
Colour	white
Specific gravity	1.03
Viscosity	330 mPas
Solid content	21%
From	liquid

2.3 Single oedometer test

Implementing the instruction provided by Jennings and Knights [19] and ASTM D5333 [20], a single collapse test was executed out on organically compacted and polymer-treated gypseous soil samples with varying polymer ratios. For quantifying the variance in compressibility attributes of gypseous soil, specimens collected fitted with a ring that measured 70 mm in diameter and 19 mm in height were used. The specimens' dry weight was determined. Preceding the test commenced, a small resting load of 5 kPa was strapped to the sample engagement ring in the frame used for loading to make sure that the sample and top cover made precise contact. After stabilizing settlement for each loading step, vertical stress was utilized progressively at 25, 50, 100, and 200 kPa. The specimen was immersed for an entire day under a vertical tension of 200 kPa. Under the consequences of a certain stress level, the collapse index can be determined employing the formula below.

$$I_c = \frac{\Delta e}{1+e_o} \quad (1)$$

where:

Δ_e= The ratio of voids before and after soaking.

I_c= Collapse Index.

e_o= starting ratio of voids.

2.4 Specimens preparation

For the production of samples for the collapse index testing, round specimens with a circumference of 70 mm and an overall height of 19 mm have been developed. To look into the consequences of the initial compacted water content on collapse, all specimens were crushed at their dry field weight units to yield roughly 76% relative density over a range of starting saturation ratios, from 20 to 90 percent.

A total of 48 samples were analyzed. For each instance of organically produced or polymer-treated soil, six samples with different saturation levels were reviewed. The average of the three studied samples was used to compute each collapse index value acquired for this inquiry to reduce the error percentage.

The soil was gradually dragged forward until the sample's elevation matched the ring elevation with little assistance. The stabilizer concentration of polymer was diluted in water before being added to the soil mixture, as shown in Figure 2(a), to ensure a homogeneous mixing of the polymer stabilizer and soil. The moisture content controlled the dilution ratio, which achieved the degree of saturation and the amount of stabilizer used. The dilution of polymer and water are added to the soil and left inside nylon bags for 24 hours at room temperature of 25°. Then, the sample is compacted using the appropriate compacting machine. Three levels of the material were added to the mold, one layer at a time. After compaction, samples were cured for seven days. The sample was created through five steps: preparing the soil, additive preparation, mixing soil and additives, molding, compaction, and curing. The dilution was added after stirring the soil for five minutes, as shown in Figure 2(b).

(a)Diluted polymer in water (b) Adding the diluted polymer to the soil

Figure 2. Specimens preparation

3. DISCUSSION OF RESULTS

3.1 Effect of initial saturation on natural gypseous soil

The variation of applied load with the void ratio for natural soil is shown in Figures 3 and 4. The collapse index fluctuates with the initial saturation level for natural gypseous soils, as shown in Figure 5. Obviously, the collapse index sharply dropped as the beginning saturation ratio increased. From the figure, it could be seen that compacted soil at an initial saturation level of 50% achieved the minimum collapse index.

This tendency can be reconciled with the realization that earlier instances of consolidation of soil with a larger initial water content disrupted the initial attachment formed by the fine-grade proportions in the soil. This decreased the soil's collapsibility. Moreover, a more significant initial water level significantly reduces the meta-stable processes, resulting in less water dropping after soaking. Nevertheless, minimal initial saturation levels are sufficient to dismantle all gypsum interconnections among soil particles entirely. Consequently, modifying the soil's structure and diminishing binding connections necessitated considerable water and effort [21]. In other words, high initial water content increases the soil deformation before socking and decreases the soil deformation after socking.

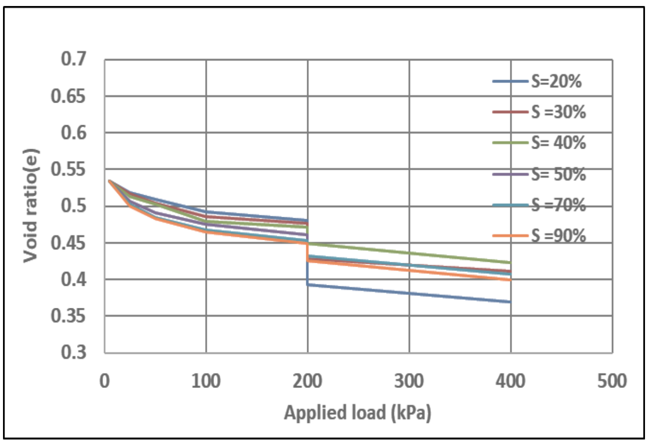

Figure 3. Applied load-void ratio relationship for natural soil (Gyp. =18%)

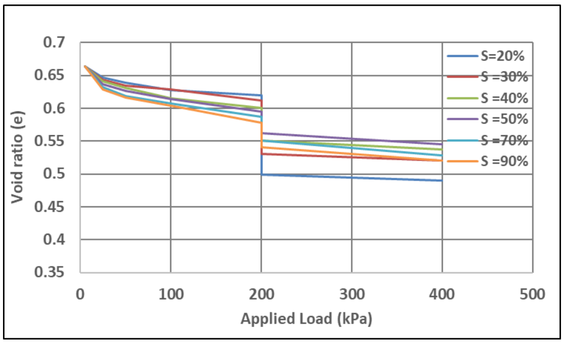

Figure 4. Applied load-void ratio relationship for natural soil (Gyp. =58%)

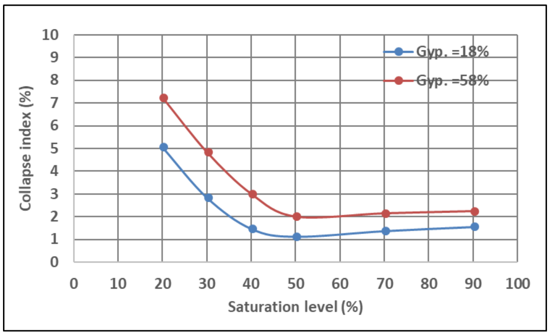

Figure 5. Collapse index - initial saturation level relationship for natural gypseous soils

3.2 Effect of initial saturation on polymer-treated gypseous soil

The fluctuation of the load imposed with the void ratio for gypseous soil cured using polymer is illustrated in Figures 6-11. The collapse index fluctuates with the initial saturation level for polymer-treated gypseous soils, as shown in Figures 12 and 13. It proved that the collapse index sharply dropped as the beginning saturation ratio increased. The optimum initial saturation level that achieves minimum collapse index is 50% for polymer-treated soil—compacted the soil at an initial saturation level of 50% and polymer content of 3%, decreasing the collapse index to 92% for soil that includes a 18% gypsum concentration and 89% for soil that includes a 58% gypsum concentration.

Increasing the initial saturation level leads to a good and homogeneous distribution of the polymer within the soil structure and, thus, a clear decrease in the collapse index. However, when the initial moisture content is less than 50%, it leads to a non-homogeneous distribution of the polymer and perhaps its agglomeration in one place rather than another, leading to a high collapse index of the soil [21].

In addition, the optimum polymer content that caused the minimum collapse index was 3%. This is the same result obtained by Mohammed et al. [4].

The collapse index dropped as polymer components increased to 3%.

The alteration of the soil may have been triggered by the aforementioned substances, which encasing the fragments of soil and increased the interaction of bonds activity. However, following a 3% polymer concentration, the polymers caused the soil particles to migrate and coagulate, which decreased the binding capacity of the soil.

The outcome was a degradation of the mass's organization and a rise in the dry unit weight, the overall amount of samples, and the collapse index.

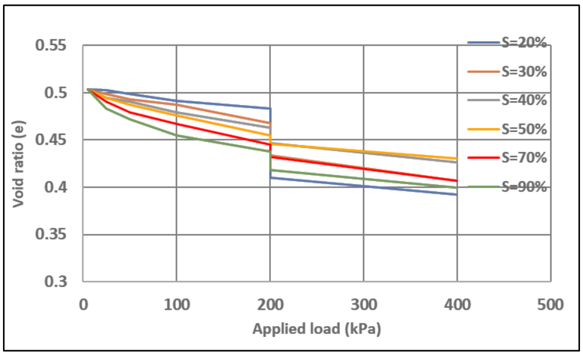

Figure 6. Applied load-void ratio relationship for polymer-treated soil (Gyp. =18%, pol. =3%)

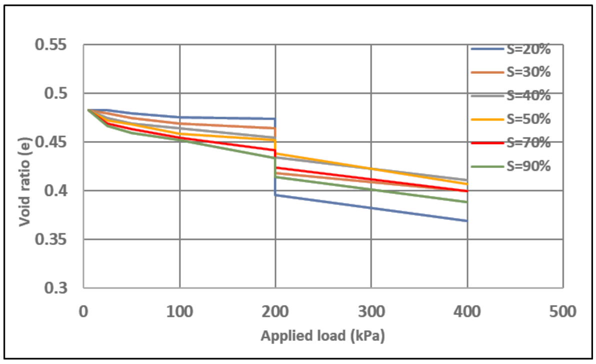

Figure 7. Applied load-void ratio relationship for polymer-treated soil (Gyp. =18%, pol. =6%)

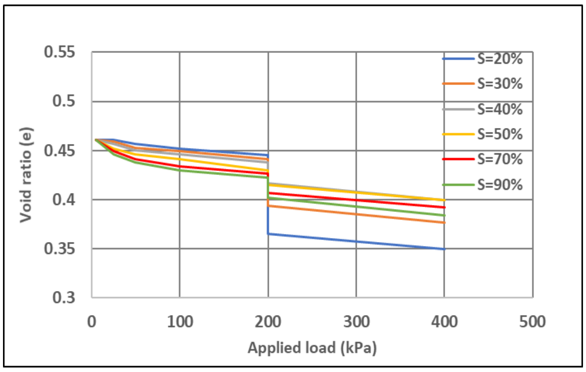

Figure 8. Applied load-void ratio relationship for polymer-treated soil (Gyp. =18%, pol. =9%)

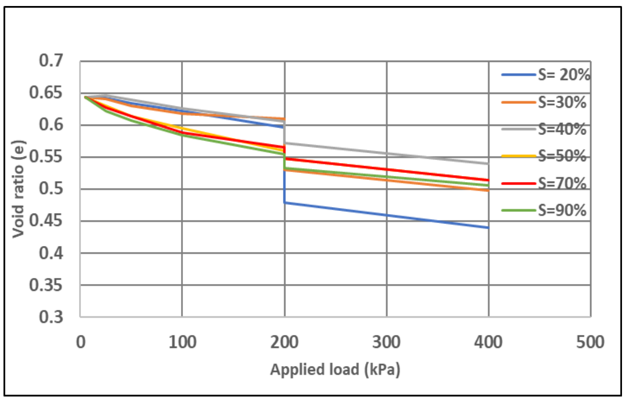

Figure 9. Applied load-void ratio relationship for polymer-treated soil (Gyp. =58%, pol. =3%)

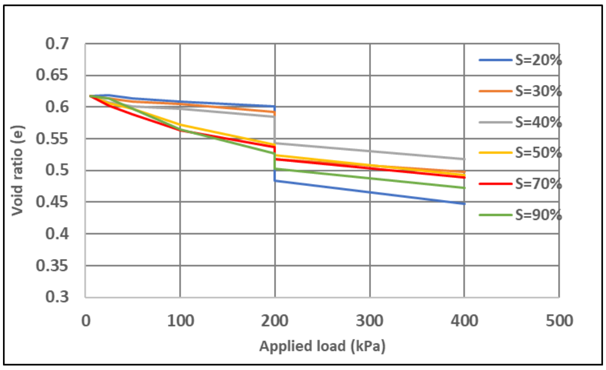

Figure 10. Applied load-void ratio relationship for polymer-treated soil (Gyp. =58%, pol. =6%)

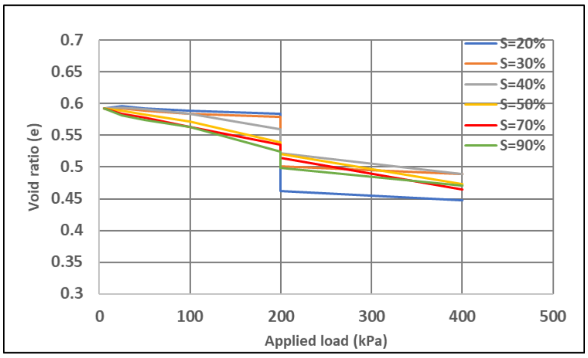

Figure 11. Applied load-void ratio relationship for polymer-treated soil (Gyp. =58%, pol. =9%)

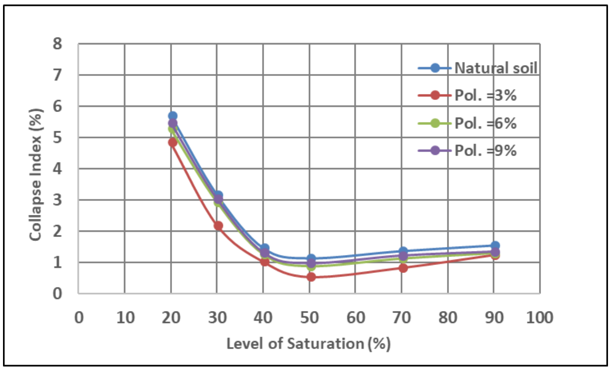

Figure 12. Collapse index-level of saturation relation (Gyp. =18%)

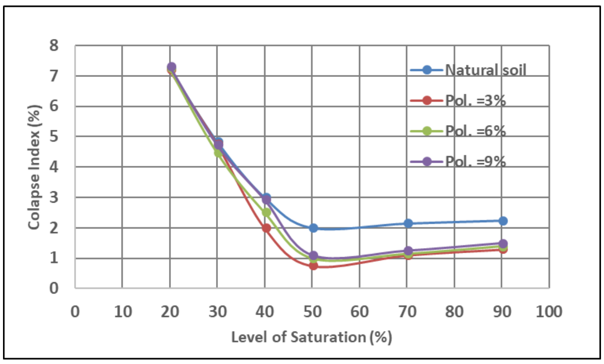

Figure 13. Collapse index-level of saturation relation (Gyp. =58%)

According to a study [21] that examined the impact of the starting moisture content on soil treated with lime and silica fume, 50% of the treated soil was the ideal irradiation ratio for minimal soil collapse. Abood et al. [22] reported that increasing the gypseous soil's water content at all saturation levels causes the angle of internal friction (ϕ, and ϕ') to decrease. Furthermore, raising the initial saturation level to 60% increases the soil's cohesiveness (c and c'). The soil's shear strength rose consequently. The initial saturation levels rose to 80% and 100%, respectively, at which point the soil's shear strength dropped.

4. STATISTICAL ANALYSIS

The data obtained from the experimental works was statistically analysed using the statistical program IBM SPSS Statistic 22. The SPSS program provides many possible mathematical models for the data entered into it. This feature helped suggest Eqs. (1) and (2) as a theoretical equation for calculating the collapse index for natural and polymer-treated gypsum. This equation incorporates all the coefficients studied during this research (Gypsum content, level of saturation, and polymer content).

$$I_c = (a + b*(\text{poly. }\%)^c + (\text{Gyp. }\%)^d)/(\text{S. }\%)^{\,d} \quad (2)$$

$$I_c = 0.633 + 779.616*(\text{pol.}\%)^{-0.011} + (\text{Gyp.}\%)^{1.596}/(\text{S }\%)^{1.788} \quad (3)$$

where,

I_c: collapse index in (%).

Pol.: polymer content in (%).

S: saturation level in (%).

Gyp.: gypsum content in soil in (%).

a, b, c, d, e: The SPSS algorithm yielded the numerical coefficients displayed in Table 3. The ANOVA analysis is shown in Table 4.

The statistical model is efficient: it explains 92.5% of the variance in the data, which means that the independent variables used in the analysis do an excellent job of explaining the variance in the dependent variable. The residual variance is relatively small: the mean squared residual (0.310) is small compared to the variance explained by the model (97.280), which means that the errors are relatively small and the model fits well. Therefore, the model used in the analysis can accurately explain most of the data. This means that most of the outcomes or changes in the dependent variable can be understood or predicted based on the independent variables used in the model.

The collapse index values from the experimental program and those from the suggested mathematical equation are likewise shown in Figure 14 clustered around a straight line predisposed at a 45° angle, demonstrating a good convergence of the values from the suggested mathematical equation.

Table 3. The SPSS algorithm yielded the numerical coefficients

Parameter Studied	Estimated Values	Standard Error Value	95% Interquartile Probability	
			Lower Limit	Upper Limit
a	0.633	0.259	0.111	1.154
b	779.616	513.634	-256.226	1815.458
c	-0.011	0.012	-0.034	0.013
d	1.596	0.171	1.521	1.941
e	1.788	0.229	1.327	2.249

Table 4. ANOVA results of the analysis

Source	Sum of Square	Df	Mean Square
Regression	486.400	5	97.28
Residual	13.316	43	0.310
Uncorrected Total	499.717	48	
Corrected Total	177.919	47	

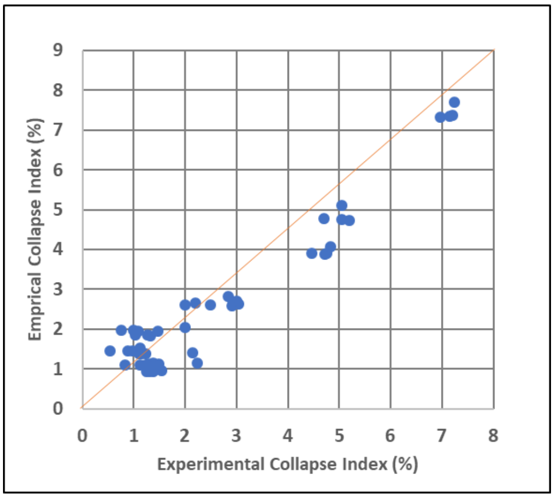

Figure 14. Experimental collapse index versus an empirical collapse index

5. CONCLUSION

1. The optimum initial saturation level that achieved minimum collapse index was 50% regarding both unaltered and polymer-treated gypseous soil. After that, the collapse index begins to increase due to decreasing soil structure stability.

2. Compacting the soil at an initial saturation level of less than 50% led to a high collapse index due to a non-homogeneous distribution of the polymer and perhaps its agglomeration in one place rather than another, thus leading to a high collapse index of the soil.

3. As the polymer ingredients are increased to 3%, the collapse index reduces and then starts to climb. This is explained by the fact that an increase in these materials weakens the mass's structure and causes it to collapse.

4. Compacted the soil at an initial saturation level of 50% and polymer content of 3%, decreasing the collapse index to 92% for soil with gypsum content of 18% and 89% for soil with gypsum content of 58%.

5. A mathematical model with a factor of assessment (R^2) of (0.925) was expected to accurately forecast the collapsibility of both natural as well as polymer-treated gypseous soil.

6. Future studies may focus on the effect of initial moisture content using other additives such as cement, fly ash, etc. They might also ascertain how the initial moisture content alters additional attributes like unconfined compression, shear characteristics, etc.

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NOMENCLATURE

Ic	Collapse index
S	Initial saturation level
e	Void ratio
Pol.	Polymer content in (%)
Gyp.	Gypsum content in soil in (%)