

Utilization of Ionic Organic Polymer to Improve Performance and Properties of Problematic Soils

Usama Heneash¹, Hossam El-Din Fawzy¹, Karima Ali¹, Ali Basha^{1*} 

¹Department of Civil Engineering, Faculty of Engineering, Kafrelshiekh University, 33511, Egypt.

Received 14 July 2023; Revised 20 November 2023; Accepted 27 November 2023; Published 01 December 2023

Abstract

Problematic soils with high compressibility and low shear strength are often treated with traditional chemical stabilizing additives such as cement and lime to improve their engineering properties. Polymers were employed to improve and reinforce a variety of material qualities in a wide range of applications. The use of polymer SBS (stabilizer base stabilizer) to improve the characteristics of problematic soils is discussed in this research. Two types of soils were used. The first type, "soil A Burj," is collapsible soil and was collected from Burj El-Arab city, while the second type, "soil B Dam," is fine sand and was obtained from Damietta city. The untreated and treated samples were subjected to sieve analysis, hydrometer, liquid limits, standard compaction, collapse potential (CP), direct shear, California Bearing Ratio (CBR) testing, and SEM, TEM, chemical, and microstructural analysis tests. Three different polymer SBS concentrations in water were used (1:300, 1:150, and 1:10). The results showed that by adding the polymer SBS, LL and OWC decreased exhibiting more plastic behavior compared to the non-treated samples. Also, the CP decreased with adding the polymer SBS, and the degree of collapsibility was enhanced from trouble to moderate trouble condition. The shear strength, internal friction angle, and CBR value were also improved. In summary, the best results were produced when a polymer ratio of 1:150 was used and a curing time of at least 28 days was provided.

Keywords: Problematic Soil; Polymer SBS; Collapse Potential; CBR; Direct Shear; Standard Compaction.

1. Introduction

The characteristics of problematic soils can be altered by changes in environmental circumstances when they are directly used for construction. Swelling or expansive clay, dispersive soils, and collapsible soils are just a few examples of problematic soils [1, 2]. Expansive and dispersive soils are briefly discussed below, followed by collapsible soils, which are the main target of this research. Dispersion occurs in soils when the diversion forces between clay particles exceed the attractive forces causing deflocculation, in which the particles repel each other to form colloidal suspensions in the presence of relatively pure water [3, 4]. Expansive soils are found primarily in dry and semiarid climates around the world. Expansive clays are difficult to work with because they swell with water absorption and shrink with adsorption. Swelling occurs when water infiltrates between clay particles, causing them to split, and such volume fluctuations induced by swelling and shrinkage movements can cause significant damage to infrastructure that is not constructed to withstand these movements [5].

Collapsible soil is stable in arid and semiarid places around the world. Collapsing soil may be identified by its abrupt volumetric drop after increasing humidity. The proportion of volumetric change under particular vertical stresses after and before water inundation is known as soil collapsing. The collapsibility is a function of various factors, including void ratio, density, soil composition, and moisture content [6, 7]. The majority of collapsible soils are silt or sand

* Corresponding author: ealibasha@eng.kfs.edu.eg

 <http://dx.doi.org/10.28991/CEJ-2023-09-12-05>



© 2023 by the authors. Licensee C.E.J, Tehran, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).

deposited by the wind. Loess is a collapsible soil deposited by the wind that covers 15-20% of Europe, China, and the United States [8].

The most common causes of soil collapse are wetness and loading. Although these soils appear to have high apparent strengths in their natural state, they typically collapse when wet or loaded because the connections that hold the grains together weaken. The rise in load, or more accurately, stress, usually results from the build-up of deposits over a lengthy period, though dynamic stresses from an event like an earthquake would give an obvious trigger mechanism, as would stress increases generated by construction activities. As something is wet, the saturation ratio often increases, frequently moving from a partially saturated state to complete saturation [9]. The mechanism of collapse attributes the formation of collapsible soils to the arid climate, where potential evaporation greatly exceeds rainfall. When the near-surface water begins to dry, capillary tension causes the remaining water to withdraw into the narrow spaces close to the soil grain interface, bringing with it soluble salts, clay colloids, and silt particles. As the soil continues to dry, the salt, clay, and silt particles come out of solution and tack weld the large soil grains together at their interface [10]. Figure 1. illustrates the main forms of collapsible soil structure.

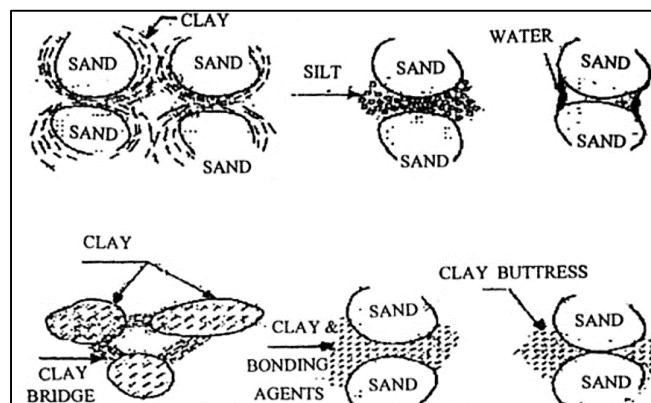


Figure 1. Main Forms of Collapsible Soil Structure [11]

Chemical soil stabilizers are generally categorized as conventional and unconventional additives. Soil stabilization is a technique introduced to improve poor soil properties in order to make them suitable for engineering projects [12]. The effect of additives on the engineering properties of soil has been studied by many researchers.

The widespread usage of traditional additives, including cement, lime, fly ash, and asphalt emulsion, led to an endeavor to find alternative non-traditional additions. The wide range of non-traditional stabilizer additives necessitated some attempts to categorize them based on their active ingredients [13, 14]. Nontraditional additives are chemical components in liquid or powder form, such as enzymes, polymers, resins, acids, silicates, ions, and lignin derivatives [15, 16]. In contrast, due to their expensive cost, the use of traditional stabilizers, such as Portland cement and lime, has often been overshadowed by the use of polymers in engineering [17–20].

In general, polymers are large compounds made up of repeating units termed monomers. Polymers are created by polymerizing monomers and have physical and chemical properties that are distinct from those of monomers. The use of both natural and synthetic polymers to stabilize soils has been documented [21–24]. In successful applications, polymers have proven to be more environmentally friendly than cement and lime in terms of greenhouse gas emissions and natural resource and energy consumption [12]. Certain polymers are abundant industrial by-products that would otherwise be discarded as waste. These include lignin, a biopolymer produced by the pulp and paper industries, and fly ash, a geopolymer precursor produced by coal power plants [26, 27].

In a study to investigate the effects of three different polyethylene (HDPE) percentages of 6, 9, and 12 on expansive clay soils, it was revealed that the liquid limit (LL), the plasticity index (PI), and the optimal moisture content (OMC) dropped as the amount of PEHD polymer increased, whereas the plastic limit (PL) increased. Moreover, the swelling potential and swelling pressure values fall dramatically at 12% PEHD. Furthermore, the CBR value increased as the amount of PEHD polymer increased. At 12% PEHD, the CBR value increased from 5.3% to 21% [28, 29].

Ayeldeen et al. (2017) examined the use of biopolymers (xanthan gum and guar gum) to improve the mechanical properties of collapsible soil [1]. Several biopolymer concentrations were utilized (0.25, 0.5, 1, and 2), and the experimental program was carried out with 0- and 7-day curing periods. The results showed that both xanthan gum and guar gum may be employed as treatment improvement materials for collapsible soil. At 2% biopolymer concentration, the collapsible potential was lowered from 9% to 1%, and the cohesiveness was improved from 8.5 to 105 kPa after one week of curing, which means an overall improvement in soil shear strength.

Mirzababaei et al. (2017) studied the effects of two chemical additions [polyvinyl alcohol (PVA) and Butane Tetra Carboxylic Acid (BTCA)] on the engineering qualities of expansive clay soil. It was concluded that PVA and BTCA greatly improved the unconfined compression strength and ductility of clay soils. Based on the findings, PVA manifested better results than BTCA in decreasing the air void ratio and water content [30].

Mousavi et al. (2014) investigated the impact of Road Packer Plus (RPP) as a polymer stabilizer for controlling swelling potential. Three RPP percentages (0.019, 0.04, and 0.06) and two curing durations (7 and 14 days) were applied. The results revealed that swelling potential and swelling pressure were improved with the addition of RPP. Soil treatment with RPP improved CBR and maximum dry density while lowering Atterberg limits. It was also discovered that the curing times had no effect on the plasticity and swelling qualities of the material. The study also concluded that the manufacturer's recommended percentage of RPP (0.019) was ineffective in minimizing swell potential; however, higher RPP content appears to be more beneficial in improving soil properties [31].

Waheed & Asmael (2018) [14] conducted laboratory tests to assess the impact of certain non-traditional additions on the engineering properties of problematic clayey soil. Polymers and phosphoric acid were chosen as unconventional stabilizers in this study at three distinct concentrations of 1, 3, and 5%. Both polymer and phosphoric acid were found to have no substantial effect on consistency limitations. For all levels of addition, however, samples treated with phosphoric acid improved their CBR values more than samples treated with polymers. It was also concluded that increasing the polymer and phosphoric acid concentrations reduced the dry density considerably while having no effect on OWC. The CBR value increased by about 360% when treated with 3% phosphoric acid compared to untreated soil. Overall, it can be claimed that phosphoric enhancement is a potential alternative that can be used to tackle geotechnical stabilizing issues. Xia et al. (2023) used the hydrophobic polymer to improve the frost resistance of soil subjected to successive freeze-thaw cycles. The experimental result showed that the hydrophobic polymers have a certain potential as a novel soil additive to improve their mechanical behavior [32].

Shafiqu & Hasan (2018) [33] tested the capacity of Polymethacrylate (PMA) polymer to enhance the prepared expansive (swelling) clayey soil in the laboratory. Bentonite was used to prepare the expanding soil. Three different percentages of PMA (3, 5, and 7) were applied by the weight of dry soil in the experimental program. The presence of PMA polymers within swelling soil induced a decrease in the LL, plasticity index (PI), and OMC. The plastic limit, maximum dry density, unconfined compression strength, and CBR, on the other hand, have all increased. The swelling potential was reduced by up to 72 percent at 7% PMA concentration, which was a significant finding. Overall, the experiments revealed that the polymers considerably reduced the issues associated with expanding soils. In the field of soil improvement utilizing non-traditional additives, only a little research has been undertaken. The aim of this study is to investigate the effect of the addition of polymer (SBS) on improving the properties of the problematic soil [34]. To achieve this purpose, experimental programming was outlined and conducted on the treated and untreated samples of two types of soils, which were collapsing silty-sand soil and poor fine-sand soil.

2. Materials

2.1. Polymer SBS

The polymer used in this investigation was SBS Superpave Base Stabilizer from the ionic organic polymer type. It was obtained from a worldwide manufacturing company in Cairo, Egypt. This polymer is commercially available and environmentally acceptable. Table 1 represents the physical and chemical properties of the polymer. It should be mentioned that the company recommends using the polymer in a diluted state with a concentration of 1/300 (1 liter is diluted by 300 liters of water). Three ratios of diluted polymer were used (1/300, 1/150, and 1/10).

Table 1. Physical and chemical properties of polymer SBS

Product Name	SBS Superpave Base Stabilizer
Hazard Storage	Not applicable
Appearance	Liquid, dark brown in colour, distinct odour
Boiling Point	182° Degrees Centigrade
Storage	5 Years
Cold Stability	Excellent
Flammability	Not Applicable
Ignition Temperature	Not Applicable
Flash Point	Not Applicable
Solubility In Water	Complete
Specific gravity	1.7
Foaming	None
Weight per liter	1.7 Kg

2.2. Soil Samples

Two types of soil are used in this research. The first is a natural collapsible soil collected from New Borg-Alarab City in the Al-Gharbaneyat area (60 km west of Alexandria), Egypt, and it was titled in this research as (soil A Burj). The second soil is fine sand collected from Damietta Governorate, Egypt, and it was titled in this research as (soil B Dam).

3. Experimental Procedures

3.1. Samples Preparation

Sample preparation is an important step in which the soils in their natural state were air dried for 15 days, ground, and sieved on sieve No.10 according to ASTM D 421-07 [35]. To understand the effect of polymer behavior on the mechanical properties of soils A and B, the initial geotechnical properties were determined according to the ASTM specifications. The physical properties of the tested soils are shown in Table 2.

Table 2. Physical properties of soils

Soil Type	Soil A (Burj)	Soil B (Dam)
% finer than 2 μ m	16%	10%
Liquid limit, L.L %	31	-
Plastic limit, P.L %	29	-
Plasticity Index, P.I %	2	-
Bulk Density/m ³	-	1.88
Specific gravity, G _s	2.68	2.66
Maximum dry unit weight/m ³	1.98	1.94
Optimum moisture content, w _c %	11.5	10.5

3.2. Mechanical Property Analysis

A total of 162 (A and B) specimens were prepared using the aforementioned method. The detailed mix design plan, the test section, and several specimens tested are tabulated in Tables 3 and 4. To understand the characteristics of problematic untreated and treated soils. The samples were kept at room temperature after drying in an oven at 100 °C and were ground and tested. The polymer was mixed with the sample in percentages by weight of the sample and with a curing time of 0 and 28 days. Figure 2 depicts the sample preparation procedure used in this study. The following laboratory tests were performed through the whole experimental program:

- Sieve analysis and hydrometer tests;
- Liquid limit test;
- Modified proctor compaction test;
- Collapsible potential test;
- Direct shear test;
- CBR test.

Table 3. Experimental Test Program (Soil A)

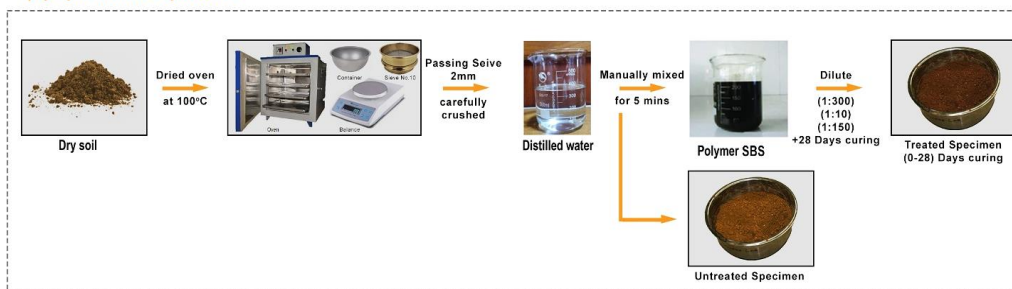
Sample ID	Material type (%by weight)		Test Performed	Number of specimens tested = 128
	Untreated	Treated		
untreated	500	0.0	Sieve & hydrometer	4
	500	0.0	L.L	4
	500	0.0	C.P %	5
	500	0.0	direct shear	5
	2000	0.0	Compaction	5
	2000	0.0	CBR	5
untreated +1:300 concentrated SBS (8-10-12-14-16) %	(492-490-488-486-484)	(8-10-12-14-16)	Liquid limit	5
	(492-490-488-486-484)	(8-10-12-14-16)	C.P %	5
	(492-490-488-486-484)	(8-10-12-14-16)	direct shear	5
	(1992-1990-1988-1986-1984)	(8-10-12-14-16)	Compaction	5
	(1992-1990-1988-1986-1984)	(8-10-12-14-16)	CBR	5
untreated +1:150 concentrated SBS (8-10-12-14-16) %	(492-490-488-486-484)	(8-10-12-14-16)	Liquid limit	5
	(492-490-488-486-484)	(8-10-12-14-16)	C.P %	5
	(492-490-488-486-484)	(8-10-12-14-16)	direct shear	5
	(1992-1990-1988-1986-1984)	(8-10-12-14-16)	Compaction	5
	(1992-1990-1988-1986-1984)	(8-10-12-14-16)	CBR	5
untreated +1:10 concentrated SBS (6-8-10-12-14) %	(492-490-488-486-484)	(8-10-12-14-16)	Liquid limit	5
	(492-490-488-486-484)	(8-10-12-14-16)	C.P %	5
	(492-490-488-486-484)	(8-10-12-14-16)	direct shear	5
	(1992-1990-1988-1986-1984)	(8-10-12-14-16)	Compaction	5
	(1992-1990-1988-1986-1984)	(8-10-12-14-16)	CBR	5

untreated +1:150 concentrated SBS (12) % With curing time 28 days	(492-490-488-486-484)	(8-10-12-14-16)	Liquid limit	5
	(492-490-488-486-484)	(8-10-12-14-16)	Compaction	5
	(492-490-488-486-484)	(8-10-12-14-16)	CBR	5

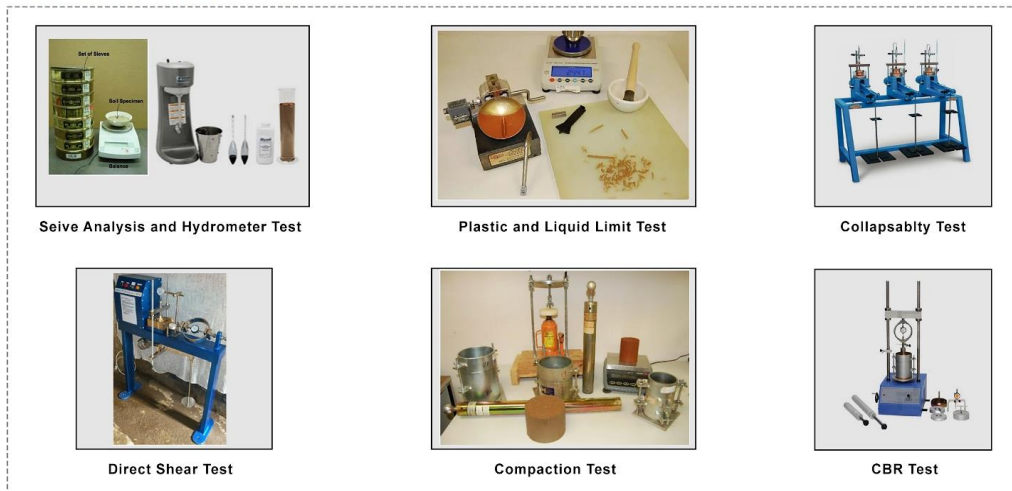
Table 4. Experimental Test Program (Soil B)

Sample ID	Material type (%by weight)		Test Performed	Number of specimens tested = 34
	Untreated	Treated		
untreated	500	0.0	Sieve	4
	500	0.0	direct shear	5
	2000	0.0	Compaction	5
	2000	0.0	CBR	5
untreated +1:300 concentrated SBS (8-10-12-14-16) %	(492-490-488-486-484)	(8-10-12-14-16)	direct shear	5
	(1992-1990-1988-1986-1984)	(8-10-12-14-16)	Compaction	5
	(1992-1990-1988-1986-1984)	(8-10-12-14-16)	CBR	5

(A) Specimen Preparation



(B) Mechanical Property Analysis



(C) Microstructural and Chemical Analysis

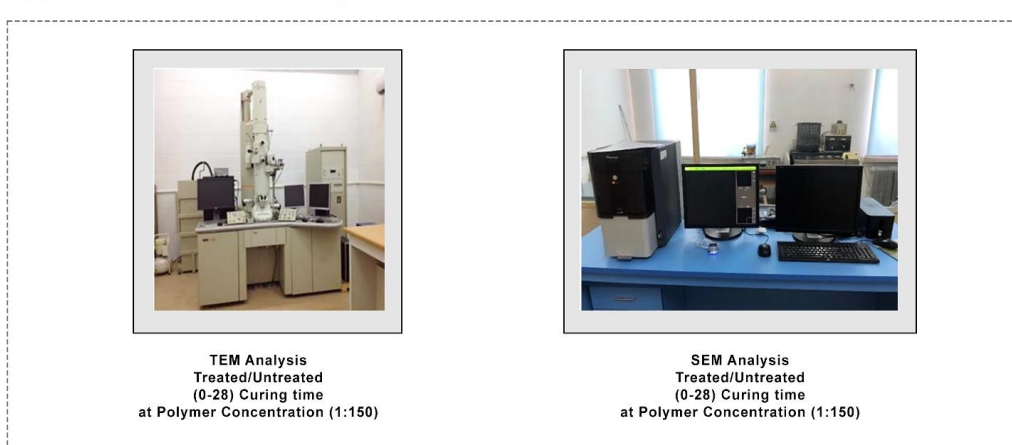
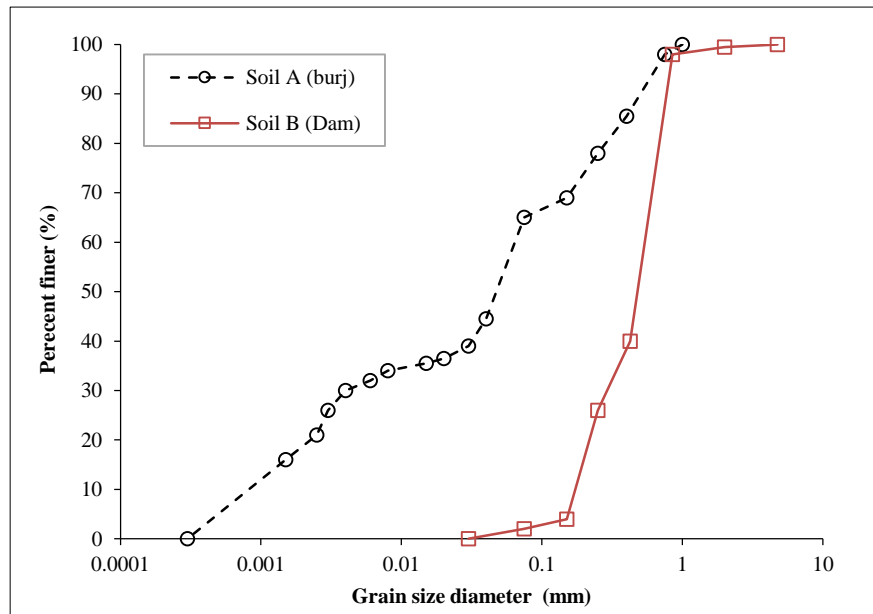


Figure 2. Procedure of specimen preparation and corresponding test apparatus

3.2.1. Sieve Analysis and Hydrometer Tests

The sieve and hydrometer tests were carried out as outlined in ASTM D 421-07 [35] and ASTM D 422-07 [36]. The grain size distribution curves for soils A and B were displayed in Figure 3. Soil A (Burj) was classified as clayey sandy silt, while soil B (Dam) was categorized as fine sand. Figure 4 shows the locations where the soil samples were collected.



Sample ID	Clay & Silt % Passing sieve No. 200	Sand %			Gravel %
		Fine	Medium	Coarse	
Particles Diameters range	< 0.075 mm	0.075-0.42 mm	0.42-2.0 mm	2.0-4.75 mm	4.75-75 mm
A (Burj)	34	20	14	0	0.00
soil B (Dam)	2	34	54	0.00	0.00

Figure 3. Grain size distribution curve of tested soils



Figure 4. Satellite depicting the location of the soil samples

3.2.2. Liquid Limit Test

A liquid limit test was applied on the treated (nature soil mixed with diluted polymer) and untreated (natural) specimens of soil A (Burj) only in accordance with ASTM-D4318 [37]. The samples were mixed with three different

polymer concentrations (1:300, 1:150, and 1:10). To investigate the effect of curing times on the performance of the treated soil, specimens were kept in sealed plastic bags for 28 days, and then subjected for testing.

3.2.3. Compaction Test

Standard modified proctor compaction test was performed on all untreated and treated samples to determine the optimum moisture content and maximum dry density according to ASTM-D 1557-91[38]. The three different polymer concentrations (1:300, 1:150, and 1:10) were specified for soil A (Burj), while the concentration ratio of 1/300 was for soil B (Dam).

3.2.4. Collapsible Potential Test

A single odometer test was performed on the treated and untreated specimens of soil A (Burj) only in order to estimate the collapsible potential in accordance with ASTM D5333-03 [39]. The collapsible potential was taken as the difference in the axial strain (%) at vertical stress of 200 kPa after and before immersing in water. The samples were mixed with three different polymer concentrations (1:300, 1:150, and 1:10).

3.2.5. Direct Shear Test

A direct shear test was carried out according to ASTM D 3080[40] to calculate shear strength parameters (cohesion and friction angle) for untreated and treated soaked samples. It was performed in a square shear box (60 x 60 x 20) mm. The three different polymer concentrations (1:300, 1:150, and 1:10) were specified for soil A (Burj), while the concentration ratio of 1/300 was for soil B (Dam).

3.2.6. CBR Test

The CBR test was conducted due to ASTM D1883 [41] in order to measure the loading capacity in the untreated and treated samples. The samples were soaked for 4 days before testing. The three different polymer concentrations (1:300, 1:150, and 1:10) were specified to soil A (Burj), which was cured for 28 days before testing, while the concentration ratio of 1/300 was for soil B (Dam) without a curing period.

4. Chemical and Microstructural Analysis

Microstructural components of SBS polymer and collapsed soil were elucidated by many sophisticated techniques, including SEM (scanning electron microscopy) and TEM (transmission electron microscopy) analysis. SEM and TEM tests were performed in the Nano Laboratory in Kafr El Sheikh after mechanical tests (compaction and CBR) of specimens of soil A (Burj) only with the optimum polymer ratio (1:150) and curing time of 28 days. The specimens were mixed with polymer and stored at room temperature after drying in an oven at 100 °C. They were then carefully crushed and tested. These direct methods are applied for particulate imaging at the nanoscale level, which provides information such as the dimension, shape, and morphology of the particles created. Figure 5. Schematic plan of the sample preparation method for soil and polymer SBS.

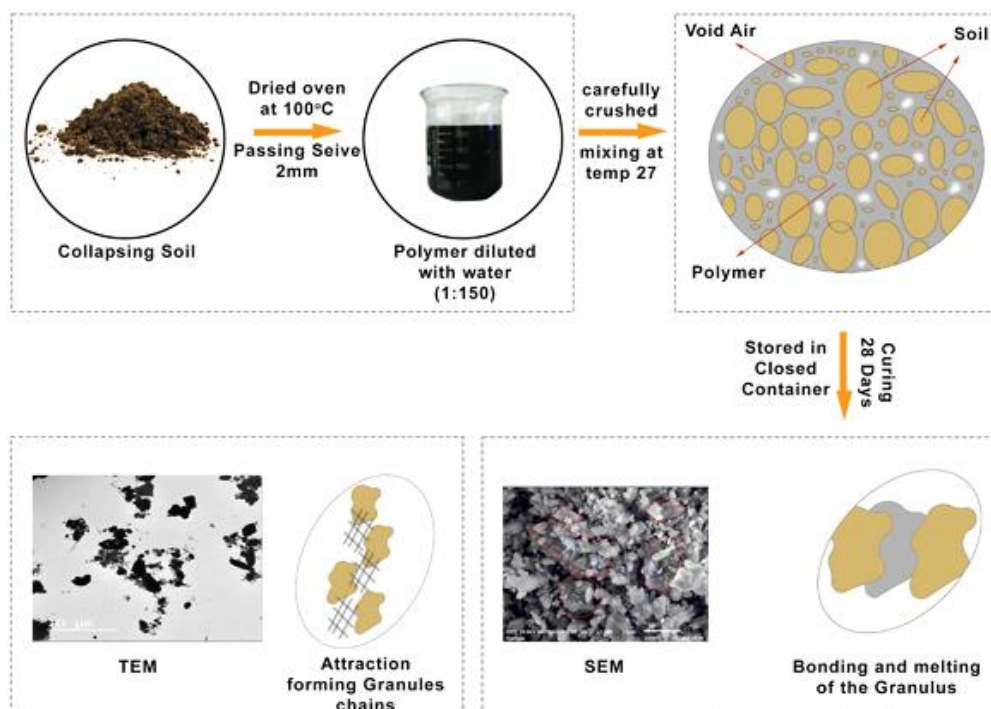


Figure 5. Schematic plan of the sample preparation method of soil and polymer SBS

5. Results and Discussion

5.1. Effect of Polymer SBS and Curing Time on LL

The liquid limits of the nature and treated soil A (Burj) are displayed in Table 5. The results showed that the LL of the nature soil was 31%. The liquid limit of samples without curing time increased at 1/300 and 1:10 concentration ratio and decreased at 1/150.

Table 5. Results of LL of soil A (Burj)

Polymer concentration (%)	Liquid limit LL (%) without curing time	Liquid limit LL (%) with 28 days of curing time
untreated	31	31
1:300	32.4	28.2
1:150	30	26.4
1:10	32	27.2

The effect of the curing period of 28 days was displayed in Table 5 as well. The table shows that the LL values decreased with the addition of polymer SBS. The lowest value occurred at 1/150 concentration ratio by 15% reduction. However, the reduction in LL was 9% and 12% occurred at 1:300 and 1:10 concentration ratios respectively. It is obvious from the table that the results of the curing period are compatible with other researchers' results in which there is considerable decrease in the value of the LL with the addition of polymer [33, 42-45]. The reason for decreasing in L.L. values with the addition of the polymer could be explained as follow. By adding the polymer, the particles agglomerate and become larger. Subsequently, the agglomerations provide less surface area and take lower water layers resulting in decreasing of the LL [33, 45, 46].

From the presented results, it can be said that the treated soils exhibited more plastic behavior compared with the non-treated sample. Moreover, when combining the polymer with the soil, it is important to consider the curing duration.

5.2. Effect of Polymer SBS on Collapsible Potential

The collapsibility behavior of the untreated and treated soil A (Burj) was assessed via an oedometer test as shown in Figure 6. The collapsible potential was calculated from Equation 1. The calculated values of the collapse potential (CP) were displayed in Table 6. Figure 6 shows the stages of the collapse potential test for all tested samples.

$$CP = \Delta H/H_0 = [\Delta e_c / (1 + e_0)] \times 100\% \tag{1}$$

where ΔH is Change in height upon wetting, H_0 is initial height, Δe_c is change in void ratio upon wetting, and e_0 is initial void ratio.

Table 6. Polymer concentration and corresponding C.P

Soil A (Burj)		
Polymer Concentration %	C.P %	Reduction factor %
0	7.06	
1/300	4.97	29 *
1/150	4.71	33
1/10	2.6	63

* 100 (7.06 - 5.01) / 7.06

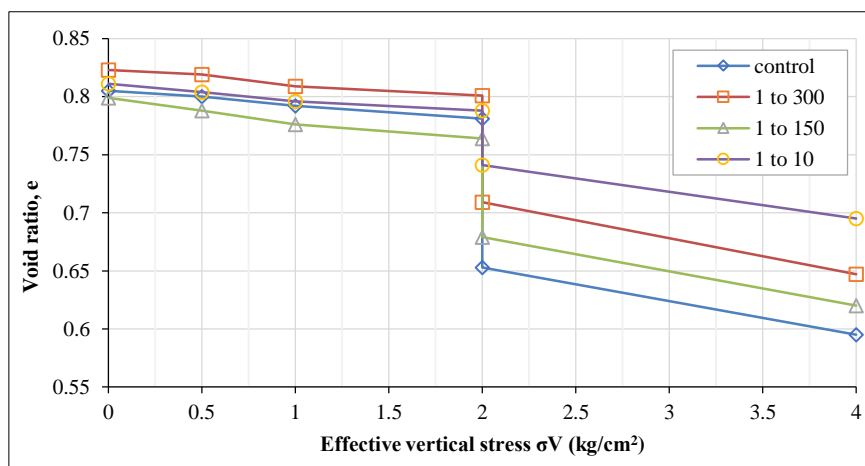


Figure 6. Oedometer test result of treated and untreated samples

From Table 6, the collapse potential for untreated soil was 7.06%, which was classified according to the severity of collapsibility as a “trouble condition” as cleared from Table 5. Table 6 also shows that the CP decreased as the polymer concentration increased for all ratios (1/300, 1:150, and 1:10). This decrease in the CP led to changing the degree of collapsibility from “trouble condition” to “moderate trouble condition,” as mentioned in Table 7.

Table 7. Potential severity of collapse

CP %	Severity of problem
0-1	no problem
1-5	moderate trouble
5-10	trouble
10-20	severe trouble
>20	very severe trouble

The third column in Table 4 shows the reduction in collapsibility with the addition of the polymer. The values of 29%, 33%, and 63% were achieved for the 1/300, 1:150, and 1:10 concentration ratios, respectively. The results are compatible with other researchers’ results, in which there is a reduction in the value of the CP with the addition of the polymer. This improvement in CP can be attributed to the nature of bonds created inside the soil matrixes by forming hydrogen bonds with low aggregation and fewer voids [1]. It can also be revealed from Table 4 that as the concentration of polymer increases, the reduction in the CP increases.

5.3. Effect of Polymer SBS on Modified Proctor

5.3.1. Soil A (Burj)

Figure 7 and Table 8 show the results of the compaction test. It is observed that the OWC values decrease with adding the polymer, except at a 1:10 concentration. Also, there was a slight increase in maximum dry density for all concentration ratios. At a 1:150 polymer concentration, the maximum dry density and minimum OWC were obtained, and the OWC decreased significantly while the maximum dry density increased just slightly.

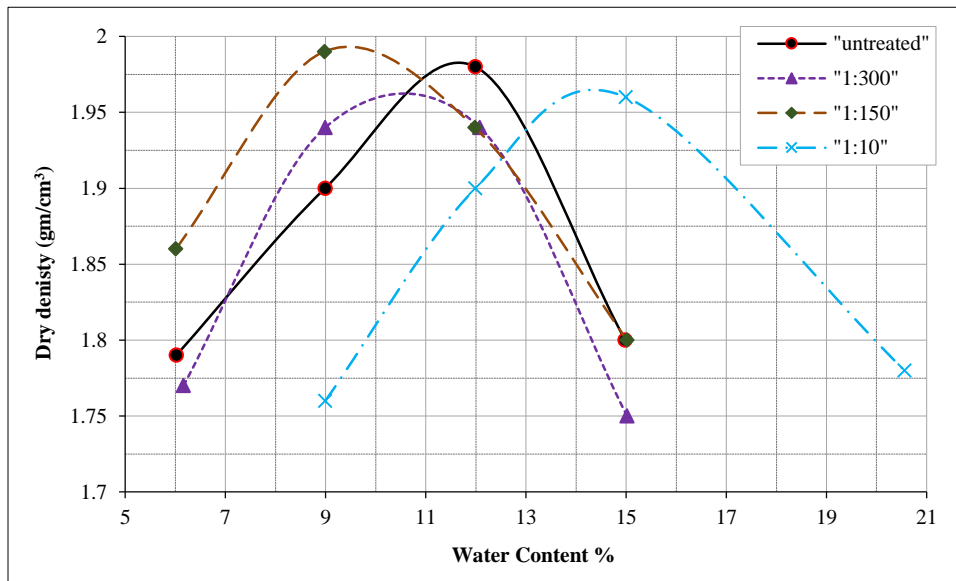


Figure 7. Results of Compaction Test for Soil (Bur)

Table 8. Maximum Dry Density and OWC % for soil A (Bur)

Polymer concentration (%)	Maximum Dry Density t/m ³	OWC %
untreated	1.96	11.5
1:300	1.96	10.5
1:150	1.99	9.5
1:10	1.97	14.3

5.3.2. Soil B (Dam)

The results of the compaction test for soil B (Dam) at only one polymer concentration percent (1/300) is shown in Figure 8 and Table 9. The maximum dry density increased by 7%, while the OWC % considerably dropped by 28%.

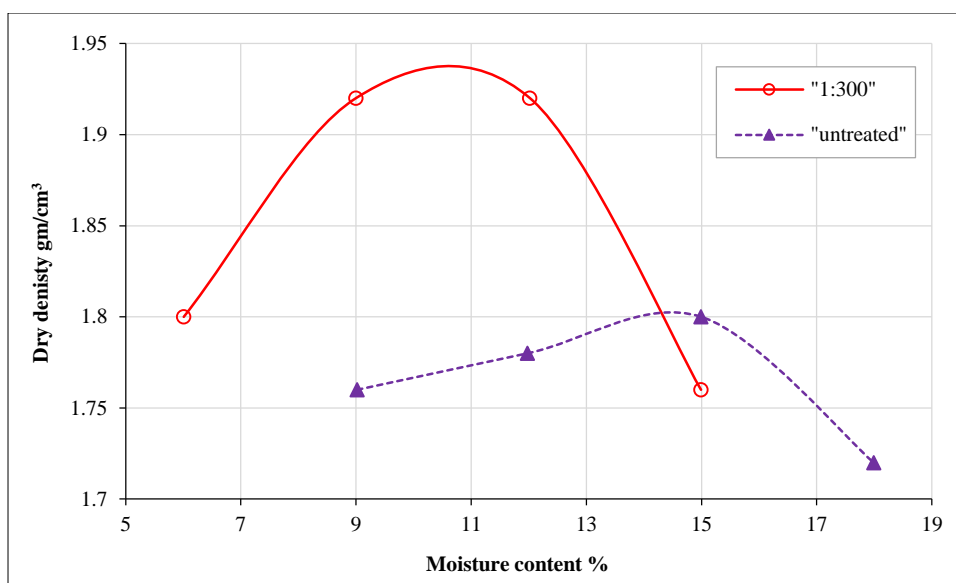


Figure 8. Result from Compaction Test for Soil B (Dam)

Table 9. Maximum Dry Density and OWC % with for soil B (dam)

Polymer concentration (%)	Maximum Dry Density t/m ³	OWC %
untreated	1.8	14.5
1:300	1.94	10.5

It should be mentioned that the provided results are compatible with other researchers' results in which there are a reduction in OWC values and an increase in the maximum dry density with adding the polymer [47]. Although the increase in maximum dry density is minor, it can be explained as a result of variations in water polarity, which causes the ionic charge of soil particles to vary. This, in turn, causes the particles to migrate significantly closer together, minimizing voids and leading to improve particles bonding and interlocking. The drop in OWC, on the other hand, could be due to the polymer within the clay samples absorbing excess water during the initial chemical reaction.

A comparison between the maximum dry density and the OWC % of soil A and soil B is presented in Table 10. From Table, it is clear that untreated soil A is denser than soil B (1.96 compared to 1.8 g/cm³). It means that soil A has less air voids than soil B. The reason for this is that soil A is a clayey-sandy-silt soil with a silt and clay particle percentage of 66 %, as shown in Figure 1. However, soil B is fine sand soil with only 12% silt and clay particles and the rest is poorly graded fine sand, as shown in Figure 1. It is also worth mentioning that the polymer's effect on increasing the density of soil B is higher than that for soil A, which was 7.7%. That is because the polymer is able to expel more voids in soil B, reducing the volume and increasing the density.

Table 10 also displays that OWC% of soil A is less than that for soil B because soil A is classified as clayey-sandy-silt soil while soil B is fine sand soil. The reduction coefficient of soil B is higher than soil A (28% compared to 8.5%). The explanation for this is that soil B has more water-filled voids, and when the polymer is added, it interacts with soil particles by encapsulating them and decreasing their water absorption, resulting in a decrease in water content.

Table 10. Comparative Soil A (BURJ) and Soil B (Dam)

Polymer Concentration	Max γ_d gm/cm ³		Promotion%		OWC		Redaction%	
	Soil A	Soil B	Soil A	Soil B	Soil A	Soil B	Soil A	Soil B
untreated	1.96	1.8	0	7.7	11.5	14.5	8.5	28
1:300	1.96	1.94			10.5	10.5		

5.4. Effect of Polymer SBS on Direct Shear Test

5.4.1. Soil A (Burj)

The results of Table 11 and Figure 9 show that the shear strength increased with the addition of polymer, with a maximum increase of 0.94 at a polymer concentration ratio of 1/150. In addition, the angle of internal friction increased for treated samples compared to untreated ones, reaching a maximum value of 32.3 at a polymer concentration ratio of 1/150. The creation of nanocomposites within the voids is attributed to the interpretation of these results, which led to an increase in the interconnection between clay particles, resulting in a homogeneous compressible isotropic material. The results also demonstrate that the cohesiveness of all soil samples (treated or untreated) is insignificant.

Table 11. Parameters for polymer-soil A (Burj)

Polymer ratio	Parameters	Specimen 1	Specimen 2	Specimen 3
untreated	γ	1.49	1.49	1.49
	Normal stress	0.5	1	1.5
	Shear stress	0.22	0.45	0.7
	C kg/cm ²		0	
	Φ°		24.9	
1 /300	γ	1.47	1.47	1.47
	Normal stress	0.5	1	1.5
	Shear stress	0.26	0.48	0.76
	C kg/cm ²		0	
	Φ°		25.8	
1 /150	γ	1.49	1.49	1.49
	Normal stress	0.5	1	1.5
	Shear stress	0.31	0.65	0.94
	C kg/cm ²		0	
	Φ°		32.3	
1 /10	γ	1.48	1.48	1.89
	Normal stress	0.5	1	1.5
	Shear stress	0.5	0.65	0.84
	C kg/cm ²		0.29	
	Φ°		26.5	

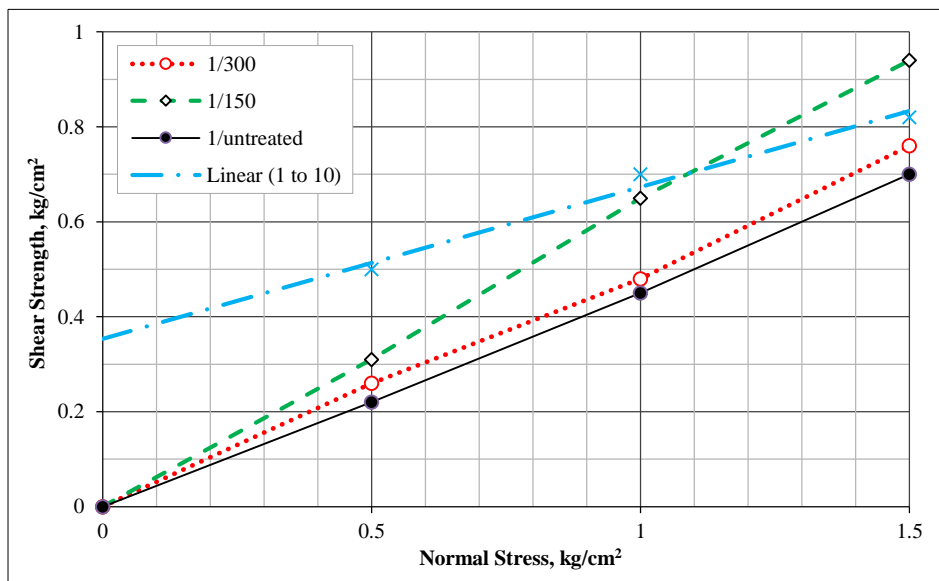


Figure 9. Direct shear test results for polymer-soil mixture (Burj) (soaked)

5.4.2. Soil B (Dam)

Table 12 and Figure 10 show the results of the direct shear test. It is worth noting that the friction angle for untreated soil was 37.29. With adding the polymer, it was noted that the friction angle increased at 1:300 polymer ratio. The findings are consistent with the findings of other researchers [1].

Table 12. Shear parameters for soil B (Dam)

Polymer ratio	Parameters	Specimen 1	Specimen 2	Specimen 3
untreated	γ	1.45	1.45	1.45
	Normal stress	0.5	1	1.5
	Shear stress	0.37	0.77	1.14
	C kg/cm ²		0	
	Φ°		37.29	

	γ	1.35	1.35	1.35
	Normal stress	0.5	1	1.5
1 / 300	Shear stress	0.41	0.84	1.25
	C kg/cm ²		0	
	Φ °		39.29	

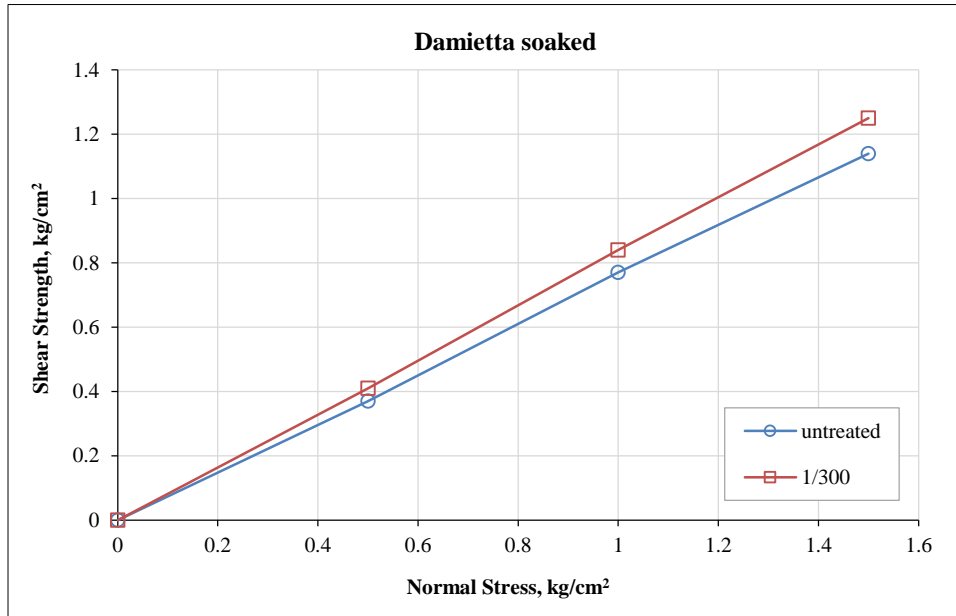


Figure 10. Direct shear test results for polymer-soil mixture (Dam) (soaked)

5.5. Effect of Polymer SBS on the CBR Ratio

5.5.1. Soil A (Burj)

Figures 11 and 12 show the raw data from the CBR test for all untreated and treated soil samples before and after 28 days curing period. Figure 13 illustrates the CBR values, which show that with the addition of polymer, the CBR value increases in all cases. Furthermore, after curing, the CBR values were higher than before curing. It is worth noting that at a 1:150 concentration, the CBR value reached the maximum with an increasing ratio of 29 % and 88 % for without and with curing time cases respectively. Overall, the findings support the significance of the curing procedure.

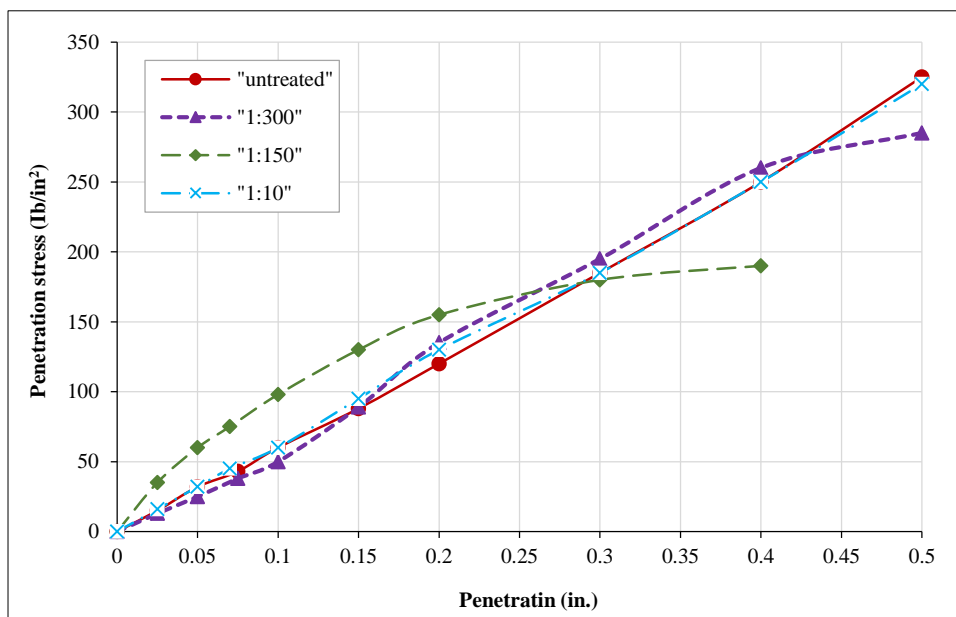


Figure 11. CBR test raw data for soil A without curing time

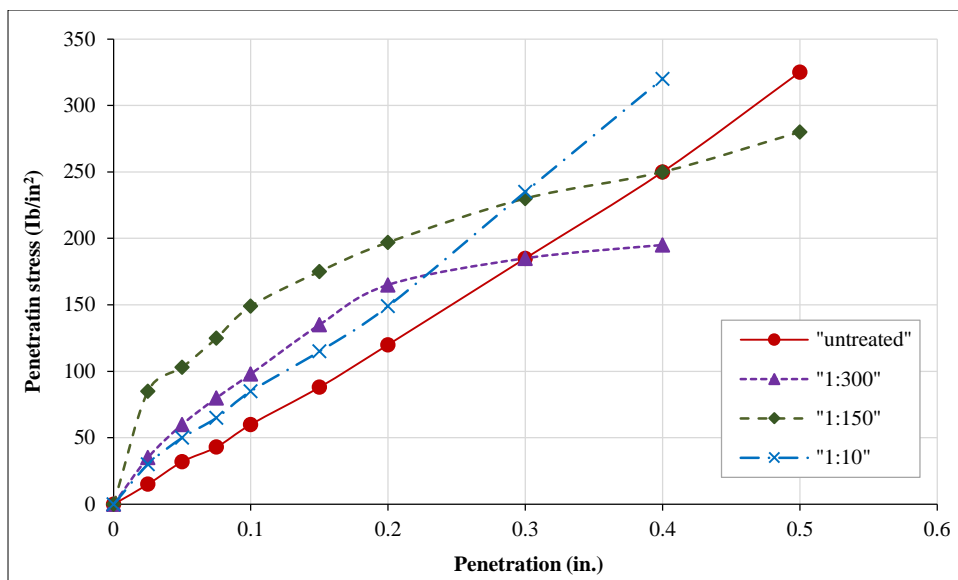


Figure 12. CBR test raw data for soil A with curing time

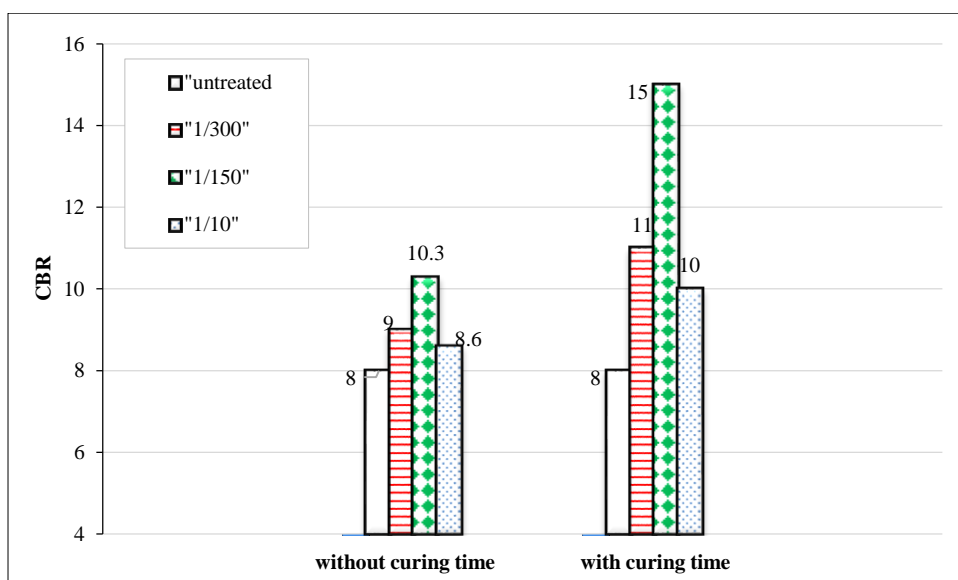


Figure 13. CBR values for Soil A (without and with curing time)

It should be noted that the natural soil was categorized as medium CBR [48], and the classification was altered to a good CBR class by adding the polymer at 1:150 concentrations for the post-curing case, as mentioned in Table 13.

Table 13. Some typical values subgrade

Classification	CBR	M _R (psi)	Typical Description
good	≥10	20000	Gravels crushed stone and sandy soils.
fair	5-9	10000	Clayey gravel and clayey sand ,fine silt soil
poor	3-5	5000	Fine silty sands, clays, silts, and organic soils

5.5.2. Soil B (Dam)

Figures 14 and 15 show the results of the CBR test on the untreated and treated samples. The CBR was determined to be 29% and 33% for untreated and treated soil, respectively. The CBR value was increased by 14% at a 1:300 polymer concentration. Although adding the polymer increased the CBR value of the treated soil, it was still categorized as a good CBR class, as mentioned in Table 12. The CBR findings are compatible with other researchers' results, in which there is an increase in CBR values with the addition of the polymer. The increase in CBR values after adding the polymer could be due to a change in the ionic charge of the clay particles, causing them to move closer together. As a result, the particles' bonding and interlocking have been improved [1, 24, 28].

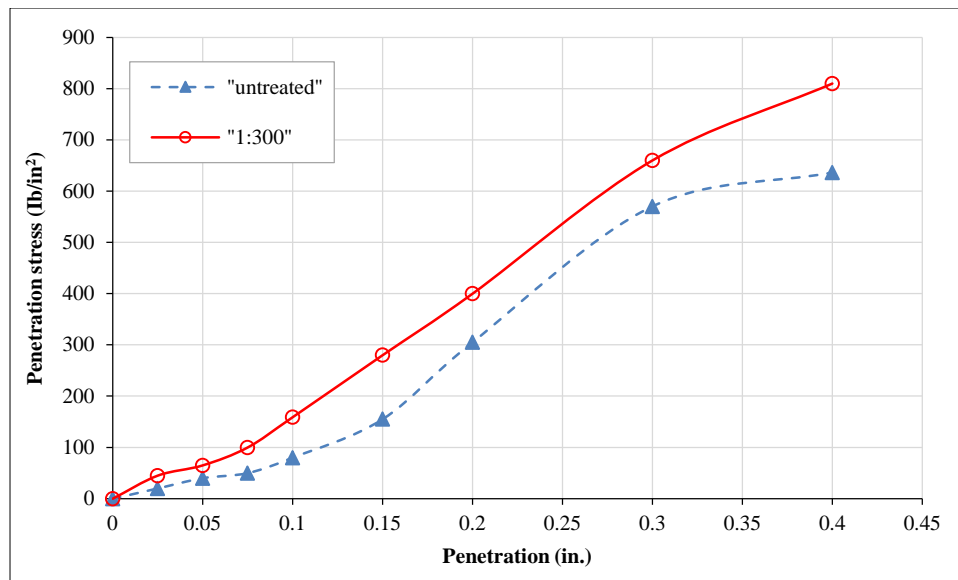


Figure 14. Raw data from the CBR test for Soil B

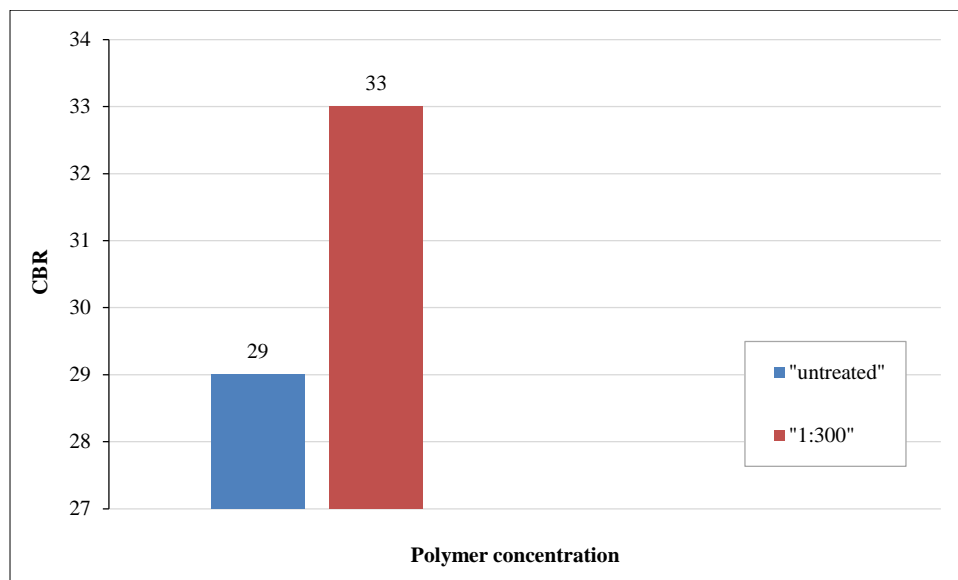


Figure 15. Influence of polymer concentration on CBR soil B

5.6. Effect of Polymer SBS Content on The Chemical Element Formation in Collapsing Soil

5.6.1. SEM Analysis

SEM images were used to investigate the effect of the SBS polymer on the soil after 28 days of curing. The SEM images shown in the microstructures in Figure 16. It was shown that the untreated soil particles have distinct borders and are mostly associated through point-to-point or point-to-surface contact. As a result, the untreated soil sample has a more porous matrix and a relatively more flexible structure, as shown. While treating soil, polymer-bound agglomerates, which are mostly composed of small particles firmly attached to surrounding particles, cover many granular pores. Moreover, face-to-face contact makes up most of the particle communication interaction. Because the treated soil sample has a denser structure and, accordingly, is more stable. The results are consistent with those of other researchers, demonstrating that the polymer has an impact on the soil that has collapsed [32, 49]. Revealed that the untreated soil particles have distinct boundaries and are typically joined point-to-point or point-to-surface. Therefore, it is unprocessed. The soil sample has a matrix with additional finely developing pores that has a somewhat loose structure. But in the treated samples using the polymer IPP, the majority of the intergranular pores are filled. The majority of the tiny particles that make up the polymer-bound agglomerates are firmly attached to the particles around them. Additionally, face-to-face contact is the primary method of connection between particles. This supports the UCS findings because the treated soil sample has a denser and thus more stable structure.

Tiwari et al. (2020) reported that the pores in the soil cavities are filled with a hydrated gel, which surrounds the soil particles to create a spatial network structure that is rather stable [50]. The dense matrix that is created when hydrated

gel forms increases the stiffness and strength of stabilized specimens. Chang et al. (2015) reported that the SEM images of clayey soils treated with xanthan gum [51]. There is a direct linkage bridge between xanthan gum and fine clay particles by hydrogen bonding; it is because of the electrically charged clay particles. In addition, bridges are formed between distant particles in xanthan gum, enhancing particle alignment and improving strength. Thus, the direct interaction is accelerated in the presence of clayey particles because of the hydrogen and ionic bonding between clay particles and biopolymers; here, it should be noted that the clay particles have electrical charges from the xanthan gum matrix (e.g., threads or textiles). Firm xanthan gum-fine soil matrices are formed by the hydrogen bonding characteristics between both of them [52]. Displayed a 7-day-cured specimen that indicates cementitious material in the form of white cooler lumps among the clay particles. The cementitious material filled most of the voids in the clay framework after 7 days of curing [53]. It shows 28 days of curing in which the clay particles were bound strongly and the new cementation products occupied the large voids. This resulted in significant changes in clay particle visibility. Khatami & O'Kelly (2013) reported that effective bonding at the microscale is primarily influenced by the kind of forces that are present at the particle/gel contact [54].

Ionic/electrostatic or covalent connections (chemisorption), hydrogen bonding (strong polar attraction), and van der Waals forces are some of the forces present at such a phase contact (physical absorption). Covalent and ionic short-range bonds have the highest bond energies (KJ/mol), making them the strongest types of bonding. The weakest bonds form over a long distance due to Van der Waals forces, which are the interactions between dipoles in the bulk material. Yet, when the molecular weight of the biopolymer grows, the viscosity of solutions often rises. On the other hand, the viscosity of solutions usually increases as the biopolymer molecular weight increases, where the higher biopolymer molecular weight has the chance to sustain crystallization of its macromolecule chain, which leads directly to increasing the degree of crosslinking inside the soil matrix. Consequently, as the guar gum has a higher viscosity solution than xanthan gum, the guar gum mixture also has a higher shear resistance than the xanthan gum mixture, as shown in Ayeldeen et al. (2017) [1]. Azzam (2014) demonstrated that the clay and polymer interacted to create a new matrix in the form of nanosizes. It suggested that the polymer was distributed uniformly throughout the clay layers [22]. The resulting nano-sized grains significantly improved the cohesiveness and net electrical attraction between neighboring grains. By creating the nanocomposites as a hydrophobic material and inhibiting the Montmorillonite's affectivity, it also improved the grain surface of the swelling clay against water. Here, the polymer transformed the soil-like nanofiller's microstructure to create a new skeleton and modified the texture of the clay by lowering the tiny particles. Additionally, it created nanocomposites inside the soil galleries. This mechanism is clearly described by the ion-change phenomenon, as demonstrated by Theng (1982) [55] and Hussain et al. (2006) [56].

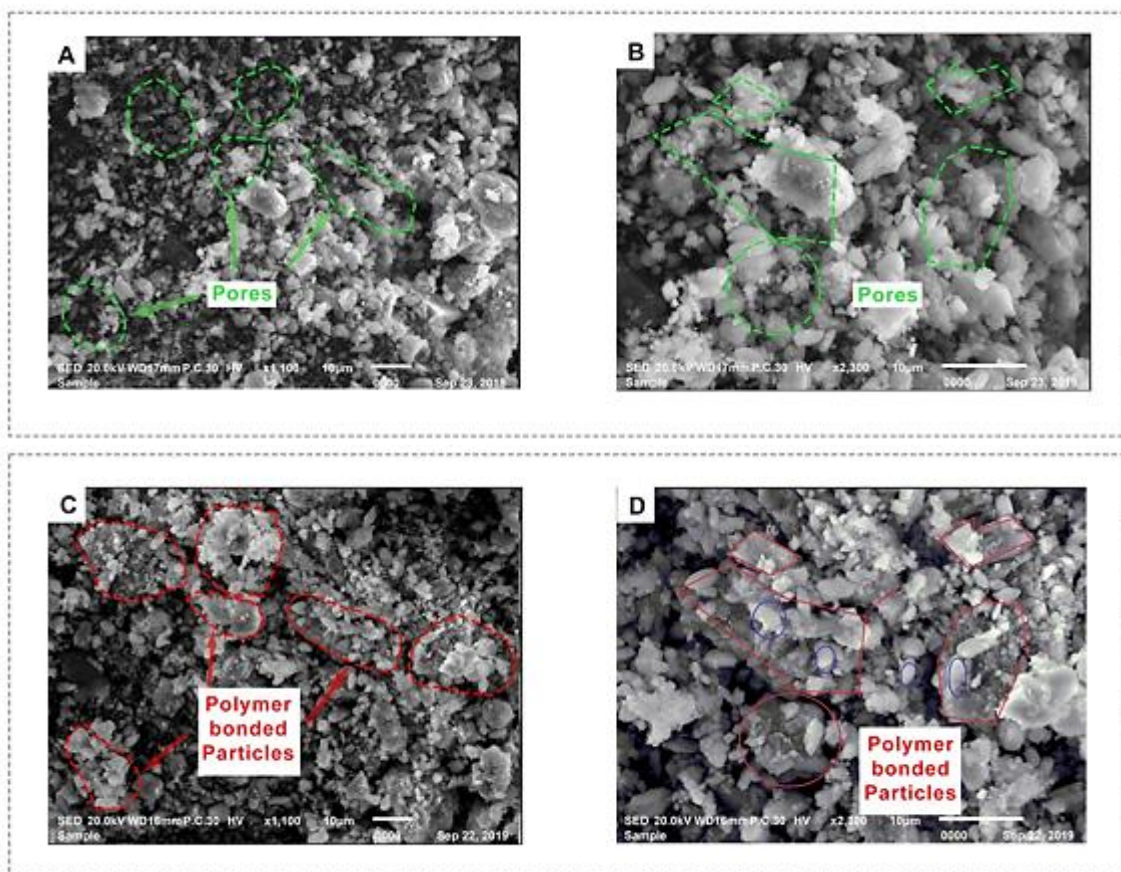


Figure 16. SEM images: (A and B) untreated sample, (C and D) treated sample at concentration polymer (1:150) with curing time 28days

5.6.2. TEM Analysis

TEM analysis was utilized to determine the size of the nanoparticles formed within the clay layer at a polymer concentration of 1:150 after 28 days of curing. The TEM images are shown in Figure 17. It has been established that the size of the nanoparticles increased with the addition of the polymer concentration. This indicated that the polymer dispersed in clay matrices, partially filling the voids, bringing the soil particles together, and binding them together to form the new filling material. TEM concluded and demonstrated the efficiency of generating the new inclusions due to an appropriate clay-polymer interaction. The outcomes are in line with those of other researchers, showing that the polymer affects the displaced soil [22].

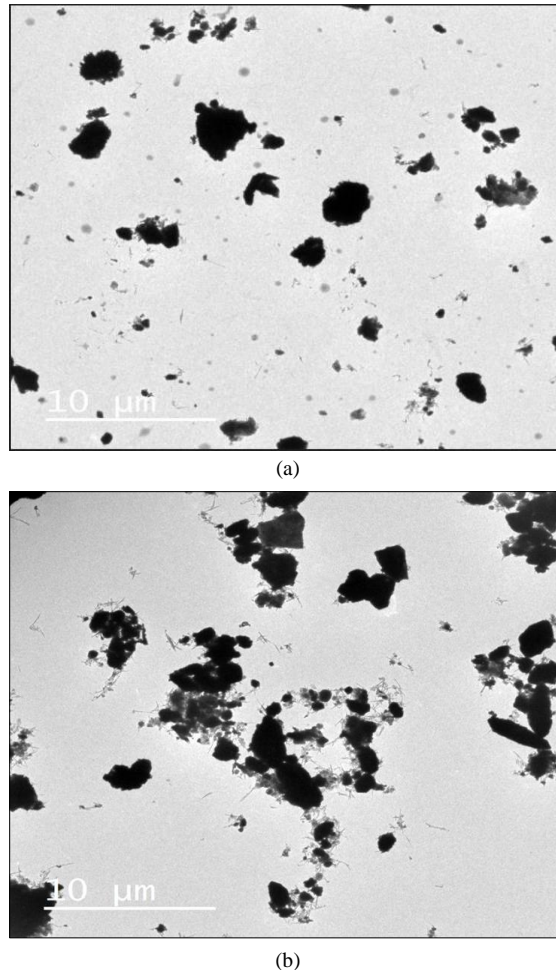


Figure 17. TEM images: (A) untreated sample, (B) treated sample at concentration polymer (1:150) with curing time 28days

6. Conclusions

Based on the results of the tests conducted throughout this research task, it can be concluded that:

- Applying a 28-day curing time led to a decrease in LL values with the addition of polymer SBS. The lowest value occurred at a 1/150 concentration ratio with a 15% reduction.
- The CP decreased as the polymer SBS concentration increased for all ratios (1/300, 1:150, and 1:10). Decreasing in the CP resulted in changing the degree of collapsibility from “trouble condition” to “moderate trouble condition”. The maximum reduction of 63% in CP occurred in the 1:10 concentration ratio.
- The high value of dry density and the low value of OWC% were obtained at a 1:150 polymer concentration. Although the OWC decreased significantly, the maximum dry density increased only slightly.
- Adding polymer enhanced shear strength and internal friction angle, with the largest increase occurring at a polymer concentration ratio of 1/150 for treated samples.
- The CBR value increases in all cases. Furthermore, after curing, the CBR values of the samples were higher than before curing. It is worth noting that at a 1:150 concentration, the CBR value reached its maximum with an increasing ratio of 29% and 88% for the cases without and with curing time, respectively.
- In summary, the best results were produced when a polymer ratio of 1:150 was used and a curing time of at least 28 days was allowed.

7. Declarations

7.1. Author Contributions

Conceptualization, U.H., H.E.F., K.A., and A.B.; methodology, U.H., H.E.F., K.A., and A.B.; formal analysis, U.H., H.E.F., K.A., and A.B.; writing—original draft preparation, U.H., H.E.F., K.A., and A.B.; writing—review and editing, A.B. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

- [1] Ayeldeen, M., Negm, A., El-Sawwaf, M., & Kitazume, M. (2017). Enhancing mechanical behaviors of collapsible soil using two biopolymers. *Journal of Rock Mechanics and Geotechnical Engineering*, 9(2), 329–339. doi:10.1016/j.jrmge.2016.11.007.
- [2] Rezaei, M., Ajalloeian, R., & Ghafoori, M. (2012). Geotechnical Properties of Problematic Soils Emphasis on Collapsible Cases. *International Journal of Geosciences*, 03(01), 105–110. doi:10.4236/ijg.2012.31012.
- [3] Umesh, T. S., Dinesh, S. V., & Sivapullaiah, P. V. (2011). Characterization of Dispersive Soils. *Materials Sciences and Applications*, 02(06), 629–633. doi:10.4236/msa.2011.26085.
- [4] Li, Z., Zhu, Z., Zhao, Y., Zeng, C., & Zhang, P. (2022). Experimental Investigation on the Diffusion Law of Polymer Slurry Grouted in Sand. *Polymers*, 14(17), 3635. doi:10.3390/polym14173635.
- [5] Katha, B. R. (2002). Shrinkage strain characterization of expansive soils using digital imaging technology. Master Thesis, The University of Texas at Arlington, Arlington, United States.
- [6] Houston, S. L., Houston, W. N., Zapata, C. E., & Lawrence, C. (2001). Geotechnical engineering practice for collapsible soils. *Unsaturated Soil Concepts and Their Application in Geotechnical Practice*. Springer, Dordrecht, Netherlands. doi:10.1007/978-94-015-9775-3_6.
- [7] Cerato, A. B., Miller, G. A., & Hajjat, J. A. (2009). Influence of Clod-Size and Structure on Wetting-Induced Volume Change of Compacted Soil. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(11), 1620–1628. doi:10.1061/(asce)gt.1943-5606.0000146.
- [8] Das, B. M., & Sivakugan, N. (2018). *Principles of foundation engineering*. Cengage Learning, Boston, United States.
- [9] Basma, A. A., & Tuncer, E. R. (1994). Evaluation and control of collapsible soils. *Journal of Geotechnical Engineering*, 120(5), 925–929. doi:10.1061/(ASCE)0733-9410(1994)120:5(925).
- [10] Abdelaziz, T. (2007). Response of Shallow Foundations resting on Collapsible Soil. Alexandria University, Bab Sharqi, Egypt.
- [11] ECP-202. (2012). Egyptian Code for Soil Mechanics—Design and Construction of Foundations. Housing and Building Research centre, Giza, Egypt.
- [12] Latifi, N., Marto, A., & Eisazadeh, A. (2016). Experimental Investigations on Behaviour of Strip Footing Placed on Chemically Stabilised Backfills and Flexible Retaining Walls. *Arabian Journal for Science and Engineering*, 41(10), 4115–4126. doi:10.1007/s13369-016-2104-8.
- [13] Oldham, J. C., Eaves, R. C., & White, D. W. (1977). Materials evaluated as potential soil stabilizers. Miscellaneous Paper S-77–15. US Army Engineer Waterways Experiment Station, Vicksburg, United States.
- [14] Waheed, M., & Asmael, N. (2018). Improvement of engineering soil properties using non-traditional additives. *MATEC Web of Conferences*, 162, 01027. doi:10.1051/mateconf/201816201027.
- [15] Blanck, G., Cuisinier, O., & Masroui, F. (2013). Soil treatment with organic non-traditional additives for the improvement of earthworks. *Acta Geotechnica*, 9(6), 1111–1122. doi:10.1007/s11440-013-0251-6.
- [16] Latifi, N., Marto, A., & Eisazadeh, A. (2015). Analysis of strength development in non-traditional liquid additive-stabilized laterite soil from macro- and micro-structural considerations. *Environmental Earth Sciences*, 73(3), 1133–1141. doi:10.1007/s12665-014-3468-2.

- [17] Orts, W. J., Roa-Espinosa, A., Sojka, R. E., Glenn, G. M., Imam, S. H., Erlacher, K., & Pedersen, J. S. (2007). Use of Synthetic Polymers and Biopolymers for Soil Stabilization in Agricultural, Construction, and Military Applications. *Journal of Materials in Civil Engineering*, 19(1), 58–66. doi:10.1061/(asce)0899-1561(2007)19:1(58).
- [18] Sojka, R. E., Bjorneberg, D. L., Entry, J. A., Lentz, R. D., & Orts, W. J. (2007). Polyacrylamide in Agriculture and Environmental Land Management. *Advances in Agronomy*, 92, 75–162. doi:10.1016/S0065-2113(04)92002-0.
- [19] Al-Khanbashi, A., Mohamed, A. M.O., Moet, A. and Hadi, B. (2000). Stabilization of desert sand using water-born polymers. In *Proc. of the First International Conference on Geotechnical, Geo-environmental Engineering and Management in arid Lands* 143 – 148, Al-Ain, United Arab Emirates.
- [20] Yang, Q. wen, Pei, X. jun, & Huang, R. qiu. (2019). Impact of polymer mixtures on the stabilization and erosion control of silty sand slope. *Journal of Mountain Science*, 16(2), 470–485. doi:10.1007/s11629-018-4905-6.
- [21] Gu, B., & Doner, H. E. (1992). The interaction of polysaccharides with silver hill illite. *Clays and Clay Minerals*, 40(2), 151–156. doi:10.1346/CCMN.1992.0400203.
- [22] Azzam, W. R. (2014). Utilization of polymer stabilization for improvement of clay microstructures. *Applied Clay Science*, 93–94, 94–101. doi:10.1016/j.clay.2014.03.006.
- [23] Georgees, R. N., Hassan, R. A., & Evans, R. P. (2017). A potential use of a hydrophilic polymeric material to enhance durability properties of pavement materials. *Construction and Building Materials*, 148, 686–695. doi:10.1016/j.conbuildmat.2017.05.086.
- [24] Liu, J., Bai, Y., Song, Z., Lu, Y., Qian, W., & Kanungo, D. P. (2018). Evaluation of strength properties of sand modified with organic polymers. *Polymers*, 10(3), 287. doi:10.3390/polym10030287.
- [25] Latifi, N., Horpibulsuk, S., Meehan, C. L., Abd Majid, M. Z., Tahir, M. M., & Mohamad, E. T. (2017). Improvement of Problematic Soils with Biopolymer-An Environmentally Friendly Soil Stabilizer. *Journal of Materials in Civil Engineering*, 29(2), 4016204. doi:10.1061/(asce)mt.1943-5533.0001706.
- [26] Lora, J. H., & Glasser, W. G. (2002). Recent industrial applications of lignin: A sustainable alternative to nonrenewable materials. *Journal of Polymers and the Environment*, 10(1–2), 39–48. doi:10.1023/A:1021070006895.
- [27] Sukmak, P., Horpibulsuk, S., & Shen, S. L. (2013). Strength development in clay-fly ash geopolymer. *Construction and Building Materials*, 40, 566–574. doi:10.1016/j.conbuildmat.2012.11.015.
- [28] Hasan, S. H., & Shafiqu, Q. S. (2017). Expansive Clayey Soil Improvement Using Polyethylene High Density Polymer. *ARNP Journal of Engineering and Applied Sciences*, 12(24), 7224-7232.
- [29] Wang, Y., Liu, J., Lin, C., Qi, C., Chen, Z., Che, W., & Ma, K. (2022). Investigation into Mechanical Behavior of Air-Hardening Organic Polymer-Stabilized Silty Sand. *Journal of Materials in Civil Engineering*, 34(11), 4022305. doi:10.1061/(asce)mt.1943-5533.0004340.
- [30] Mirzababaei, M., Arulrajah, A., & Ouston, M. (2017). Polymers for Stabilization of Soft Clay Soils. *Procedia Engineering*, 189, 25–32. doi:10.1016/j.proeng.2017.05.005.
- [31] Mousavi, F., Abdi, E., & Rahimi, H. (2014). Effect of polymer stabilizer on swelling potential and CBR of forest road material. *KSCE Journal of Civil Engineering*, 18(7), 2064–2071. doi:10.1007/s12205-014-0137-7.
- [32] Xia, W., Wang, Q., Yu, Q., Yao, M., Sun, D., Liu, J., & Wang, Z. (2023). Experimental investigation of the mechanical properties of hydrophobic polymer-modified soil subjected to freeze–thaw cycles. *Acta Geotechnica*, 18(7), 3623–3642. doi:10.1007/s11440-023-01804-9.
- [33] Shafiqu, Q. S. M., & Hasan, S. H. (2018). Improvement an Expansive Soil using Polymethacrylate Polymer. *IOP Conference Series: Materials Science and Engineering*, 454, 012138. doi:10.1088/1757-899x/454/1/012138.
- [34] Geng, L., Liu, Y., Xu, Q., Han, F., Yu, X., & Qin, T. (2021). Development of bio-based stabilizers and their effects on the performance of SBS-modified asphalt. *Construction and Building Materials*, 271, 121889. doi:10.1016/j.conbuildmat.2020.121889.
- [35] ASTM D421. (2007). Standard Practice for Dry Preparation of Soil Samples for Particle-Size. ASTM International, Pennsylvania, United States.
- [36] ASTM D422. (2007). Standard Test Method for Particle-Size Analysis of Soils. ASTM International, Pennsylvania, United States.
- [37] ASTM D4318. (2018). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, Pennsylvania, United States. doi:10.1520/D4318-17E01.
- [38] ASTM D1557. (2021). Standard Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³)). ASTM International, Pennsylvania, United States. doi:10.1520/D1557-12R21.

- [39] ASTM D5333. (1996). Standard test method for measurement of collapse potential of soils. ASTM International, Pennsylvania, United States. doi:10.1520/D5333-92R96.
- [40] ASTM D3080-04. (2012). Standard Test Method for Direct Shear Test of Soils under Consolidated Drained Conditions. ASTM International, Pennsylvania, United States. doi:10.1520/D3080-04.
- [41] ASTM D1883-21. (2021). Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils. ASTM International, Pennsylvania, United States. doi:10.1520/D1883-21.
- [42] Rajoria, V., & Kaur, S. (2015). Effect of polymer stabilizer on the geotechnical properties of black cotton soil. 50th Indian Geotechnical Conference, 17-19 December, 2015, Pune, India.
- [43] Dai, D., Peng, J., Wei, R., Li, L., & Lin, H. (2022). Improvement in dynamic behaviors of cement-stabilized soil by super-absorbent-polymer under cyclic loading. *Soil Dynamics and Earthquake Engineering*, 163, 107554. doi:10.1016/j.soildyn.2022.107554.
- [44] Zhu, X., Liu, J., Xue, J., Zhang, F., Chen, Z., Hu, G., & Jiang, C. (2022). Effect of Curing Condition on the Compressive Mechanical Behavior of Clayey Soil Stabilized with Liquid Polymer. *International Journal of Polymer Science*, 2022. doi:10.1155/2022/9031369.
- [45] Mpofu, P., Addai-Mensah, J., & Ralston, J. (2004). Flocculation and dewatering behaviour of smectite dispersions: Effect of polymer structure type. *Minerals Engineering*, 17(3), 411–423. doi:10.1016/j.mineng.2003.11.010.
- [46] Anderson, R. L., Ratcliffe, I., Greenwell, H. C., Williams, P. A., Cliffe, S., & Coveney, P. V. (2010). Clay swelling - A challenge in the oilfield. *Earth-Science Reviews*, 98(3–4), 201–216. doi:10.1016/j.earscirev.2009.11.003.
- [47] Bell, F. G. (2013). *Engineering properties of soils and rocks*. Elsevier, Amsterdam, Netherlands. doi:10.1016/C2013-0-01182-6.
- [48] NAPA. (1999). Guidelines for use of HMA overlays to rehabilitate PCC pavement. National Asphalt Pavement Association (NAPA), Greenbelt, United States.
- [49] Shu, H., Yu, Q., Niu, C., Liu, J., Xia, W., Sun, X., ... & Wang, Q. (2023). Effect of dry-wet cycles on the mechanical properties of saline soil solidified with sulfur-free lignin and hydrophobic polymer. *Journal of Building Engineering*, 107116. doi:10.1016/j.jobe.2023.107116.
- [50] Tiwari, N., Satyam, N., & Singh, K. (2020). Effect of Curing on Micro-Physical Performance of Polypropylene Fiber Reinforced and Silica Fume stabilized Expansive Soil under Freezing Thawing Cycles. *Scientific Reports*, 10(1), 7624. doi:10.1038/s41598-020-64658-1.
- [51] Chang, I., Im, J., Prasadhi, A. K., & Cho, G. C. (2015). Effects of Xanthan gum biopolymer on soil strengthening. *Construction and Building Materials*, 74, 65-72. doi:10.1016/j.conbuildmat.2014.10.026.
- [52] Nugent, R. A., Zhang, G., & Gambrell, R. P. (2009). Effect of Exopolymers on the Liquid Limit of Clays and Its Engineering Implications. *Transportation Research Record: Journal of the Transportation Research Board*, 2101(1), 34–43. doi:10.3141/2101-05.
- [53] Chang, I., & Cho, G. C. (2012). Strengthening of Korean residual soil with β -1,3/1,6-glucan biopolymer. *Construction and Building Materials*, 30, 30–35. doi:10.1016/j.conbuildmat.2011.11.030.
- [54] Khatami, H. R., & O’Kelly, B. C. (2013). Improving Mechanical Properties of Sand Using Biopolymers. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(8), 1402–1406. doi:10.1061/(asce)gt.1943-5606.0000861.
- [55] Theng, B. K. G. (1982). Clay-Polymer Interactions: Summary and Perspectives. *Clays and Clay Minerals*, 30(1), 1–10. doi:10.1346/ccmn.1982.0300101.
- [56] Hussain, F., Hojjati, M., Okamoto, M., & Gorga, R. E. (2006). Review article: Polymer-matrix nanocomposites, processing, manufacturing, and application: An overview. *Journal of Composite Materials*, 40(17), 1511–1575. doi:10.1177/0021998306067321.