Improving the Engineering Properties of Highly Expansive Soil by adding Psyllium Seed Biogel

Sondos Kareem Al-Mousawi
Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
sondos@uomustansiriyah.edu.iq (corresponding author)

Shaimaa Hasan Fadhil
Department of Civil Engineering, College of Engineering, Mustansiriyah University, Baghdad, Iraq
dr.shaimaah@uomustansiriyah.edu.iq

Received: 18 October 2024 | Revised: 3 November 2024 and 15 November 2024 | Accepted: 20 November 2024

 DOI: https://doi.org/10.48084/etasr.9329

ABSTRACT

This study investigates the use of environmentally sustainable materials, particularly biopolymers, to enhance the engineering properties of expansive soils. Psyllium Seed (PS) biogel, added in four percentages, 0.4%, 0.8%, 1.2%, and 1.6% by dry weight of soil, was evaluated as a biopolymer additive for highly expansive soil. A series of tests were conducted on treated and untreated soil samples. The results revealed a slight decrease in the Atterberg limits with 1.6% PS biogel, where the liquid limit (LL) reached 75.3%, the plastic limit (PL) dropped to 32.65%, and the plasticity index (PI) was reduced to 42.65%. The swelling potential decreased significantly by 76% at 1.6% PS biogel. Compressibility improved with a 52.3% reduction in the compression index (Cc) and a 96% reduction in the recompression index (Cr) at 1.6% PS biogel content. The Unconfined Compressive Strength (UCS) increased, with the best improvement being observed at 0.8% PS biogel (81.6%), and continued enhancement with longer curing periods. Elasticity also improved, with the strain at failure increasing by 83.75% at 1.2% PS biogel. The SEM analysis confirmed that 0.8% PS biogel rearranged the clay particles and reduced voids, leading to enhanced UCS and reduced swelling. These findings highlight the PS biogel as an environmentally sustainable and effective material for improving the engineering properties of expansive soils.

Keywords-expansive soil; biopolymer; biogel; swelling; psyllium seed biogel; swelling presure; sustainable materials

I. INTRODUCTION

Expansive soils are among the most problematic soil types in civil engineering, known for causing significant damage to structures. Unlike other soil types, expansive soils exhibit unique swelling and shrinkage behaviors due to their high clay mineral content and sensitivity to moisture fluctuations. These behaviors lead to structural issues, particularly in lightweight constructions, such as uplifted buildings, cracks in walls and ceilings, and damage to pipelines, sidewalks, and pathways [1]. Expansive soils are natural, highly plastic, and highly dispersed. They undergo significant volume changes with variations in water content during wet and dry seasons [2]. Over the years, numerous amendments and treatments have been developed to stabilize these soils and make them suitable for construction projects. Soil stabilization technologies have seen significant advancements in the past decade [3]. However, the persistent challenges associated with expansive soils have highlighted the necessity for innovative and sustainable stabilization techniques. Recently, environmentally friendly stabilizers, such as polymers, biopolymers, and geopolymers, have gained attention for their ability to enhance engineering properties, like compressive strength and workability, while minimizing the environmental impact of traditional stabilizers, such as cement-based additives [4]. Generally, adding polymer materials to soil by specific percentages of its dry weight enhance its unconfined compressive strength UCS significantly, since adding strips of waste plastic material which made of polymers was highly improved the UCS of a clayey sand soil mixture [5]. For instance, authors in [6] demonstrated that using Xanthan Gum (XG) in soil stabilization reduced the soil's maximum dry density, increased its optimal water content, and quadrupled the UCS while reducing compressibility by 65% after 28 days. Similarly, authors in [7] found that 2.5 % Guar Gum (GG) increased the compressibility index of soil by 1.36 times, attributed to an enhanced repulsion between the soil particles and the hydroxyl groups of GG.

Other biopolymer studies have shown promising results. In [8], researchers observed an 85% reduction in swelling pressure and a 100% increase in shear strength with an addition of up to 3% agar biopolymer after seven days of curing. Additionally, in [9], it was found that incorporating 2% Sodium Alginate (SA) biopolymer, reduced the swelling potential and improved the undrained shear strength of expansive soil. In

[10], authors highlighted the benefits of Waste Marble Dust (WMD) and Corncob Ash (CCA), reporting a 322.65% increase in UCS, a rise in California Bearing Ratio (CBR) values from 1.68% to 15.53%, and reductions in the PI, LLs, and free swell. Other studies have explored innovative stabilization materials, such as Bluegum Sawdust Ash (BSDA) and Sisal Fiber (SF), which improved the PI, UCS, and CBR values significantly [11]. Authors in [12] investigated the use of Coconut Shell Ash (CSA) as a partial cement replacement in compressed earth blocks, showing improvements in dry density, water absorption, and compressive strength.

Despite these advancements, there is a noticeable gap in the study of biogels for improving expansive soils. This study explores the potential of PS biogel, a cost-effective and environmentally friendly material, to enhance the engineering properties of expansive soils.

II. EXPERIMENTAL WORK

A. Materials

1) Expansive Soil

The soil used in this study is an artificially prepared mixture comprising natural clayey soil and Bentonite. The natural soil was obtained from a site in the west of Baghdad Governorate at a depth of 2 meters. The prepared soil mixture consisted of 70% natural soil and 30% Bentonite by weight. Standard tests were conducted to determine the physical and chemical properties of the mixed soil [13-17]. The results of these tests are summarized in Table I.

TABLE I. PHYSICAL AND MECHANICAL PROPERTIES OF THE MIXED SOIL

Properties	Magnitude	Specification
The Specific Gravity(Gs)	2.7	ASTM D854-14 [14]
LL %	86.45	BS 1377-2 [15]
PL %	37.94	ASTM D4318-17e1 [16]
PI%	48.51	ASTM D4318-17e1 [17]
Optimum Moisture Content OMC (%)	15.37	ASTM D698-12 [13]
Maximum Dry Unit Weight (kN/m^3)	16	ASTM D698-12 [13]
Swelling Potential %	13.5	ASTM D4546-03 [17]

Note: The samples for Swelling potential and q_u tests were prepared at dry unit weight of 15.44 kN/m3 and water content of 13.79 % which represents a sample at the dry side of the compaction curve

2) Psyllium Seed

Psyllium refers to several members of the plant genus Plantago, as illustrated in Figure 1(a). Commercial producers utilize PSs to extract mucilage, which is obtained by mechanically milling the seed coat's outer layer. This mucilage forms a gel-like substance upon absorbing water. Psyllium is recognized as a medicinally active natural polysaccharide and has been widely used in various medical treatments. Previous studies have focused on fractionating the polysaccharide from the seed husk and evaluating its gelling properties. However, there is limited research on the properties of the polysaccharide present within the seeds themselves. Figure 1(b) depicts the PS [18].

(a) (b)

Fig. 1. Images of (a) genus Plantago plant and (b) PSs.

B. Specimen Preperation

The prepared soil was mixed with four different percentages of PS biogel: 0.4%, 0.8%, 1.2%, and 1.6% by the dry weight of the soil. The PS biogel was extracted by boiling PS in distilled water for 10 minutes. This specific boiling duration was determined after multiple trials to achieve a sufficient thick gel. The extracted PS biogel was then used as a partial replacement for the designated water content chosen for each test [19]. Figure 2 depicts the prepared PS biogel.

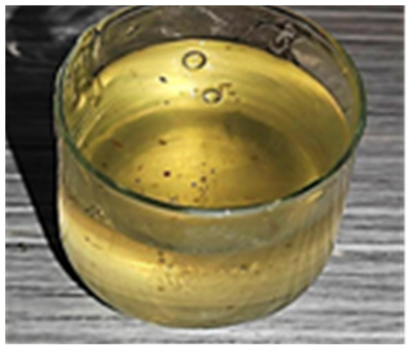

Fig. 2. The prepared PS biogel.

III. RESULTS AND DISCUSSION

A. Compaction Test

A standard Proctor test was performed in accordance with ASTM D698-12 [13] to evaluate the maximum dry unit weight and Optimum Moisture Content (OMC) for each increment of PS in the soil mixture. The results of the standard Proctor test are presented in Figure 3.

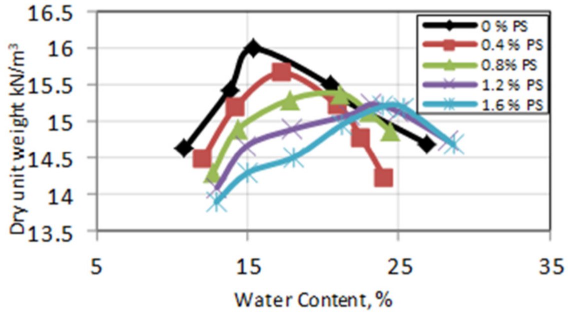

Fig. 3. Standard protocol test results.

The OMC increased significantly, rising by 55.5% from 15.37% to 23.9%, while the maximum dry unit weight decreased by 5% from 16 kN/m^3 to 15.21 kN/m^3 This trend, as portrayed in Figure 4, shows that the dry unit weight of the soil decreases as the PS biogel content increases, whereas the OMC increases. The reduction in maximum dry density is attributed to two factors: the replacement effect, where the gel replaces a portion of the soil and has a specific gravity lower than that of the soil and the water absorption, where chemical reactions involving the PS biogel absorb water, leading to an increase in OMC and a decrease in dry unit weight.

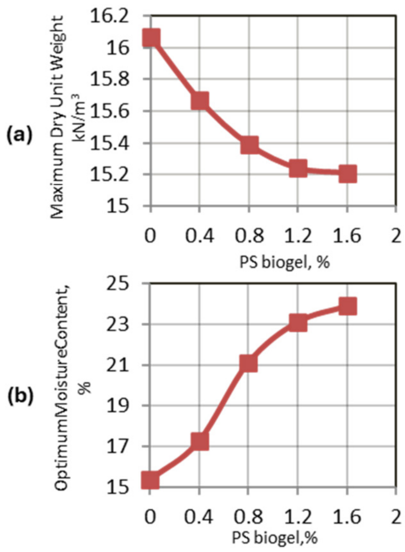

Fig. 4. Variation in (a) maximum dry unit weight (kN/m³) and (b) OMC (%), with different percentages of PS biogel.

B. *Specigic Gravity*

The Specific Gravity (Gs) test was conducted following ASTM D854-14 [14], with distilled water having been used as the test medium. The results of the test are displayed in Figure 5.

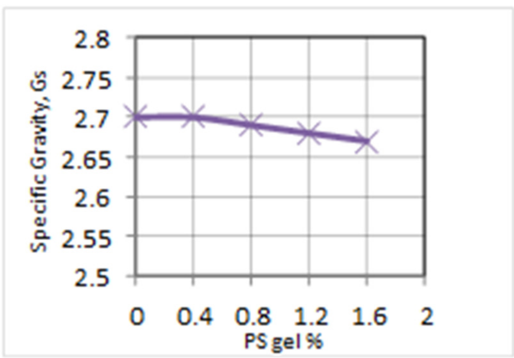

Fig. 5. Variation in G_s of expansive soil with different percentages of PS biogel.

The addition of PS biogel caused a slight reduction in the G_s of the prepared expansive soil, which decreased to 2.67 at 1.6% PS gel. This reduction is attributed to the lower specific gravity of the PS biogel compared to the mineral components of the soil. When mixed with soil, the biogel reduces the overall density of the mixture, leading to a decrease in G_s. The reduction in G_s offers several advantages: reduced self-weight, minimized swelling and settlement, and improved drainage stability.

C. *Atterberg's Limits*

The LL was determined using the cone penetrometer method, as described in BS 1377-2, while the PL was measured following ASTM D4318-17e1 [15, 16]. The effect of incorporating PS biogel into the prepared expansive soil on Atterberg's limits is shown in Figure 6. The preliminary results indicate a slight reduction in both the LLs and PLs with the addition of 1.6% PS biogel, with decreases of 13% and 14%, respectively. This, in turn, resulted in a 12% reduction in the PI.

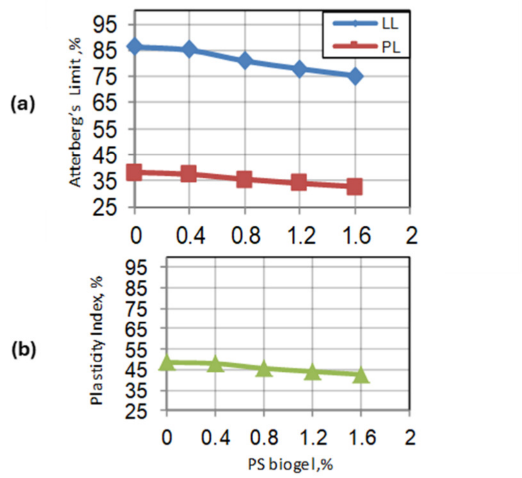

Fig. 6. Variation in (a) Atterberg's limits (%) and (b) PI (%), with different percentages of PS biogel.

D. *Swelling Potential-Swelling Pressure*

The swelling test was performed on both the treated and untreated soil samples in accordance with ASTM D4546-03 [17]. Numerous studies have identified two main groups of factors influencing swelling pressure: internal factors, such as pore water properties, specific surface area of clay, and cation exchange capacity, and external factors, including water content, compaction techniques, and dry density [20]. The sample was prepared with a dry unit weight of 15.44 kN/m^3 and a water content of 13.79%, which places it on the dry side of the compaction curve. Figure 7 illustrates the relationship between the swelling and time for both the treated and untreated expansive soil. The effect of the varying PS biogel content on the swelling potential of the prepared expansive soil is presented in Figure 8. Table II summarizes the results for the swelling pressure and swelling potential for both treated and untreated soil samples. It is evident that the addition of PS biogel significantly reduced both the swelling potential and swelling pressure of the soil. Specifically, with the addition of 1.6% PS biogel, the swelling potential decreased by 76%, and the swelling pressure was reduced by 75%. This reduction is attributed to the viscosity of the PS biogel, which acts as a binder, effectively binding clay particles together and increasing the cohesion of the soil. Consequently, this reduction in particle movement leads to a decrease in swelling and swelling pressure.

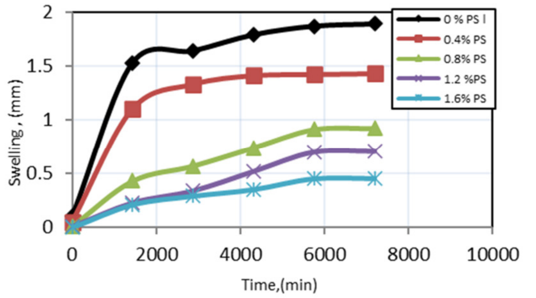

Fig. 7. Relationship between swelling and time for prepared expansive soil with varying percentages of PS biogel.

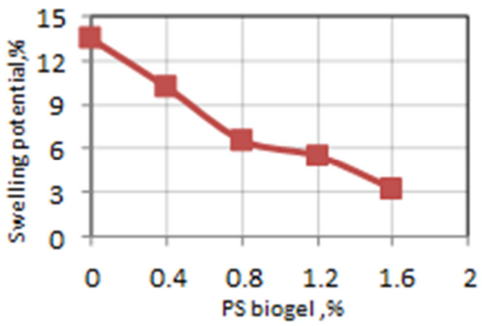

Fig. 8. Variation in swelling potential % of expansive soil with different percentages of PS biogel.

TABLE II. RESULTS OF SWELLING POTENTIAL AND PRESSURE

Sample	PS Biogel %	Swelling Potential (%)	Swelling Pressure (kPa)
1	0	13.5	244
2	0.4	10.2	183
3	0.8	6.57	134.2
4	1.2	5.5	97.6
5	1.6	3.23	61

E. Consolidation Test

The consolidation test was conducted in accordance with ASTM D2435/D2435-11 [21]. The sample was prepared with a dry unit weight of 15.44 kN/m³ and a water content of 13.79%, placing it on the dry side of the compaction curve. Stresses of 50, 100, 200, and 800 kPa were applied incrementally every 24 hours in a sequence of $\Delta P/P = 1$, where P represents the applied stress. Dial gauge readings were recorded over time. Figure 9 illustrates the C_c and C_r. It can be observed that both the C_c and C_r values decreased as the PS biogel content increased to 1.6%, with C_c reducing from 0.17 to 0.081 and C_r decreasing from 0.493 to 0.019. The presence of the PS biogel between the clay particles leads to particle rearrangement, which reduces voids and increases cohesion, thus decreasing the compressibility of the soil.

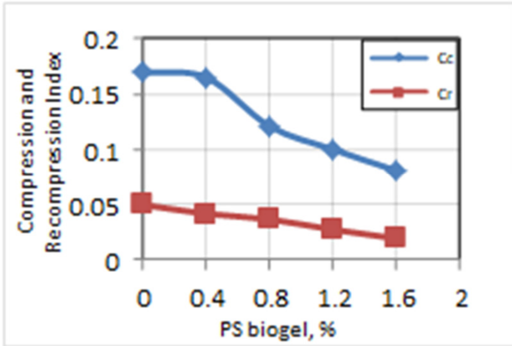

Fig. 9. Variation in C_c and C_r with different percentages of PS biogel.

F. Unconfined Compressive Strength

The UCS test was conducted according to ASTM D2166-06 [22]. Both the untreated and treated soil samples were tested. The samples were prepared with a dry unit weight of 15.44 kN/m³ and a water content of 13.79%, placing them on the dry side of the compaction curve. Each sample was placed in a mold with a height of 8.5 mm and a diameter of 40 mm, then extracted from the mold and cured for varying periods of 0, 7, and 14 days at room temperature (approximately 25°C). After the curing period, the samples were tested for UCS. The results are portrayed in Figure 10 and Table III. The failure stress was determined as either the peak stress or the stress at 20% strain, whichever occurred first.

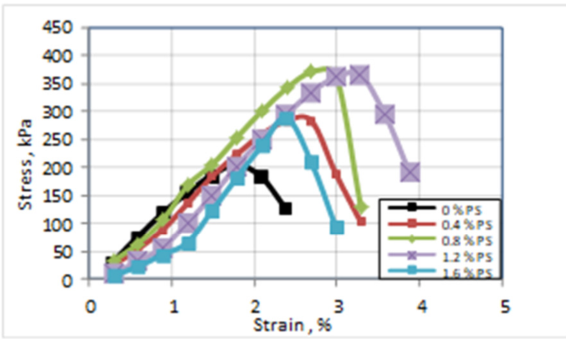

Fig. 10. Stress-Strain relationship for prepared expansive soil with different percentages of PS biogel.

TABLE III. UNCONFINED COMPRESSIVE TEST RESULTS

PS Biogel (%)	UCS (qu) (kPa)	Failure Strain ($\mathcal{E}$) (%)	Modulus of Elasticity (E_s) (kPa)
0	204.51	1.785	131.286
0.4	283.345	2.69	136.222
0.8	370.84	2.69	140.265
1.2	355.22	3.28	161.92
1.6	288.349	2.39	184.542

The addition of PS biogel significantly enhanced the UCS of the prepared expansive soil, as well as the modulus of elasticity (E_s) and strain ($\mathcal{E}$). The UCS values increased substantially with increasing the PS biogel content. The maximum improvement was 81.6% when 0.8% PS biogel was added to the soil mixture. However, the UCS began to decrease slightly with higher PS biogel percentages, as shown in Figure 11(a). Moreover, a notable improvement in the ductility of the prepared soil was observed. The *E* increased by 40% with 1.6% PS biogel, while the strain, which was required to reach failure, increased by 83.75% at 1.2% PS biogel. These results indicate that PS biogel plays a substantial role in enhancing the soil's elasticity and deformability. Additionally, the curing period had a positive effect on UCS, as demonstrated in Table VI and Figures 11(b), 12, and 13. After 7 days of curing, the UCS increased by 90.6% for the untreated soil and by 117% for the soil treated with 0.8% PS biogel. After 14 days, the enhancement rose to 137.6% for the untreated soil and 172% for the soil with 0.8% PS biogel. This improvement can be attributed to the bonding properties of the PS biogel, which act as a binder between the clay particles. Additionally, the water absorption capacity of the PS biogel helps draw and converge the soil particles, enhancing the overall strength of the soil structure.

(a)

(b)

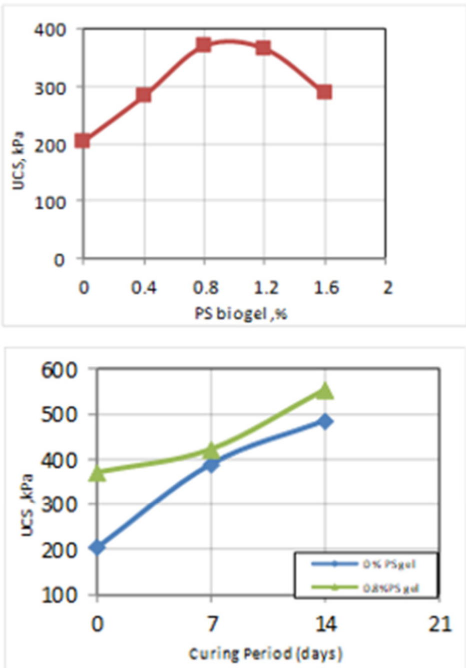

Fig. 11. UC of soil treated with PS biogel at (a) different percentages and (b) different curing periods.

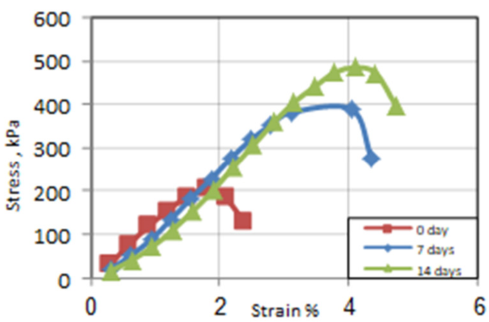

Fig. 12. Stress-Strain relationship for prepared expansive soil at different curing periods.

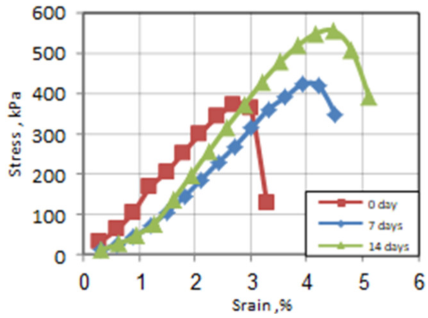

Fig. 13. Stress-Strain relationship for prepared expansive soil treated with 0.8% PS biogel at different curing periods.

TABLE IV. UNCONFINED COMPRESSIVE STRENGTH TEST RESULTS AT DIFFERENT CURING PERIODS

PS Biogel (%)	UCS (*qu*) (kPa) at 0 days	UCS (*qu*) (kPa) at 7 days	UCS (*qu*) (kPa) at 14 days
0	204.51	389.2	484.77
0.8	370.84	422.2	554.5

G. Scanning Electron Microscope Test

Scanning Electron Microscopy (SEM) tests were performed on both untreated and treated soil samples with 0.8% PS biogel to observe the impact of the PS gel on the microstructure of the prepared expansive soil. As evidenced in Figure 14, the addition of the PS biogel significantly altered the structure of the treated soil.

(a)

(b)

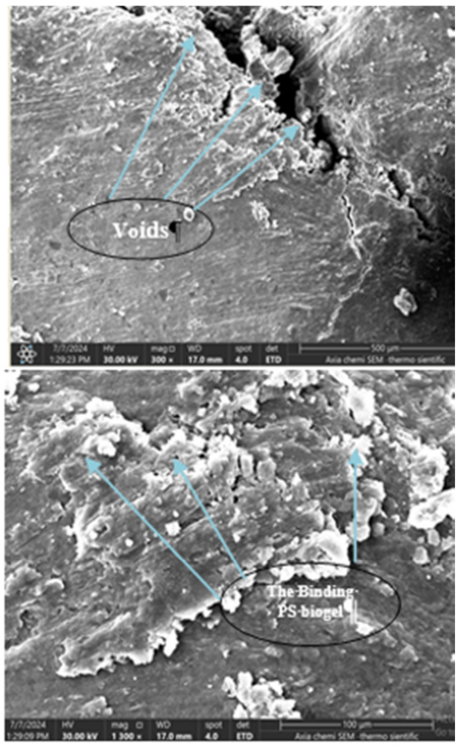

Fig. 14. SEM test of (a) untreated sample and (b) treated sample with 0.8% PS gel.

The results revealed a reduction in the void ratio in the treated soil, as the PS biogel acts as a binder, facilitating the cohesion of the soil particles. This binding effect led to a notable improvement in the clay behavior of the soil.

H. Fourier Transform Infrared Spectrometry Analysis

The Fourier Transform Infrared Spectrometry (FTIR) analysis was conducted on untreated soil and soil treated with 0.8% PS biogel to identify changes in functional groups associated with improved soil characteristics. The resulting spectra are depicted in Figure 15. The analysis aimed to investigate the correlation between the functional group modifications and enhancements in the soil behavior.

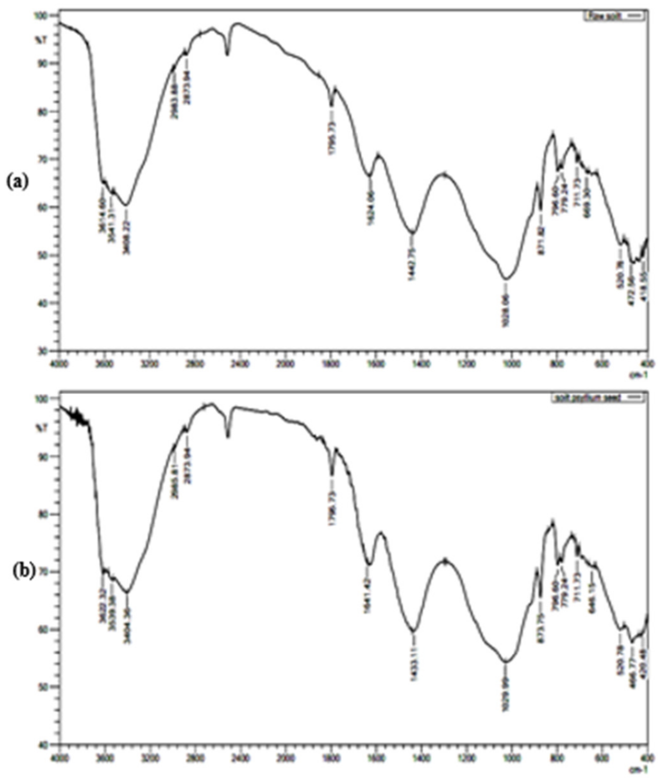

Fig. 15. FTIR analysis for (a) prepared expansive soil and (b) prepared expansive soil with 0.8% PS biogel.

The preliminary results indicate an increase in specific functional groups after treatment. The peaks observed at the wave numbers 3622.32, 3539.38, and 3404.36 cm⁻¹ represent phenolic hydroxyl groups (O-H stretching) [23], which are involved in chemical reactions resulting in hydrogen bonds with soil particles. These bonds enhance cohesion and improve soil matrix stability, making the soil less susceptible to expansion. A weak peak at 2985.81 and 2873.94 cm⁻¹ corresponds to the symmetric stretching vibrations of methyl (-CH_3) groups. These hydrophobic groups influence the electrostatic charges and cohesion in the soil, reducing its liquidity and improving its structural stability. Despite their hydrophobic nature, the presence of weak hydrophobic groups suggests that the soil still retains some hydrophilic properties, allowing it to mix with water [24]. A weak peak at 1795.73 cm⁻¹ corresponds to (C=O) anhydride bonds, contributing to soil structure modification and reduced plasticity, while 1641.42 cm⁻¹ represents weak alkene (C=C) bonds that stabilize the soil structure and enhance strength. The peak at 1433.11 cm⁻¹ is attributed to CH group bending vibrations, often associated with plant tissues and polymers, aiding structural reinforcement [25]. At 1029 cm⁻¹, the stretching vibrations of (C–O) bonds indicate alcohols, ethers, and esters, which act as binders between the particles, reducing plasticity and improving cohesion. Additionally, strong peaks at 873.75, 796.6, 779.24, and 711.73 cm⁻¹ are linked to (C-Cl) bonds; 646.51 and 520.78 cm⁻¹ to (C-Br) bonds; and 466.77 and 420.48 cm⁻¹ to (C-I) bonds, all of which influence the soil's physical and chemical properties, including its swelling behavior. Overall, these functional groups introduced by the PS biogel enhance soil cohesion, reduce plasticity, and improve stability.

IV. CONCLUSION

This study investigated the effects of adding Psyllium Seed (PS) biogel to expansive soils, highlighting its potential as a natural, sustainable additive to improve soil stability and reduce its swelling behavior. The findings demonstrate that the PS biogel significantly enhances the engineering properties of expansive soils, presenting promising implications for geotechnical applications. The key results are summarized as follows:

- Compaction Properties: Adding PS biogel reduced the dry unit weight by 5% and increased the Optimal Moisture Content (OMC) by 55.5%.
- Specific Gravity (Gs): The soil's Gs decreased to 2.67 at a PS biogel content of 1.6%.
- Atterberg Limits: A slight decrease in liquid limits (LLs) and plastic limits (PLs) resulted in a reduction of the Plasticity Index (PI) with the addition of PS biogel.
- Swelling Behavior: The swelling potential of the soil decreased by 76% with 1.6% PS biogel, demonstrating its effectiveness in mitigating expansive behavior.
- Compressibility: The PS biogel reduced compressibility significantly, with compression and recompression indices (C_c and C_r) decreasing from 0.17 to 0.081 and 0.493 to 0.019, respectively, at 1.6% biogel content.
- Unconfined Compressive Strength (UCS): The UCS and modulus of elasticity (E) improved, with the highest UCS enhancement of 81.6% having been observed at 0.8% PS biogel. These enhancements continued to improve with longer curing periods.
- Ductility: The modulus of elasticity increased by 40% at 1.6% PS biogel, while the strain at failure rose by 83.75% at 1.2% PS biogel.
- Microstructural Changes: The Fourier Transform Infrared Spectrometry (FTIR) and Scanning Electron Microscopy (SEM) analyses confirmed significant improvements in soil structure. The SEM images showed uniform clay particle distribution and binding gel formation, while the FTIR

analysis identified functional groups that enhanced cohesion, reduced plasticity, and improved soil stability.

In conclusion, using PS biogel as a soil stabilizer for expansive soils offers a novel, eco-friendly solution for expansive soil treatment. Its natural swelling and water-absorbing properties improve soil structure while minimizing environmental impact compared to conversional stabilizers, like lime or cement. The biopolymer's polysaccharide content enhances soil behavior by reducing swelling potential, increasing stability, and boosting load-bearing capacity. This innovation demonstrates potential as a sustainable, low-cost alternative for infrastructure projects in regions with challenging expansive soils, offering accessibility and reduced ecological impact for developing areas.

ACKNOWLEDGMENT

This study is supported by the College of Engineering at Mustansiriyah University.

REFERENCES

[1] J. Nelson and D. J. Miller, *Expansive Soils: Problems and Practice in Foundation and Pavement Engineering*, Hoboken, New Jersey, United States: John Wiley & Sons, 1997.

[2] F. H. Chen, *Foundations on Expansive Soils, Amsterdam, Netherlands:* Elsevier, 2012.

[3] S. Kolias, V. Kasselouri-Rigopoulou, and A. Karahalios, "Stabilisation of clayey soils with high calcium fly ash and cement," *Cement and Concrete Composites*, vol. 27, no. 2, pp. 301–313, Feb. 2005, https://doi.org/10.1016/j.cemconcomp.2004.02.019.

[4] L. A. Al-Jaberi, A. Ali, R. S. Al-Jadiri, and Z. Al-Khafaji, "Workability and Compressive Strength Properties of (Fly Ash-Metakaolin) based Flowable Geopolymer Mortar," *Electronic Journal of Structural Engineering*, vol. 23, no. 4, pp. 46–51, Dec. 2023, https://doi.org/10.56748/ejse.23436.

[5] S. H. Fadhil, M. S. Al-Soud, and R. M. Kudadad, "Enhancing the strength of clay-sand mixture by discrete waste plastic strips," *Journal of Applied Science and Engineering*, vol. 24, no. 3, pp. 381-391, Jun. 2021, https://doi.org/10.6180/jase.202106_24(3).0013.

[6] J. R. Joga and B. J. S. Varaprasad, "Sustainable improvement of expansive clays using xanthan gum as a biopolymer," *Civil Engineering Journal*, vol. 5, no. 9, pp. 1893–1903, 2019.

[7] K. V. Vydehi and A. A. B. Moghal, "Compressibility Characteristics of Guar Gum-Treated Expansive Soil," in *Ground Improvement and Reinforced Soil Structures*, Singapore, 2022, pp. 339–345, https://doi.org/10.1007/978-981-16-1831-4_31.

[8] N. Kantesaria, P. Chandra, and A. Sachan, "Stabilization of Expansive Soil Using Agar Biopolymer," *IFCEE 2021*, vol. 82, no. 4, pp. 272–281, May 2021, https://doi.org/10.1061/9780784483411.026.

[9] M. Elkenawy, A. Gabr, and M. G. Arab, "Mechanical Properties of Unsaturated Expansive Soils Treated with Eco-Friendly Sodium Alginate Biopolymer," *International Journal of Geosynthetics and Ground Engineering*, vol. 9, no. 3, Jun. 2023, Art. no. 34, https://doi.org/10.1007/s40891-023-00452-z.

[10] L. Z. Wongbae, C. Kabubo, and A. Owayo, "The Effect of Waste Marble Dust and Corncob Ash on the Engineering and Micro-Structural Properties of Expansive Soil for Use in Road Subgrades," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13765–13772, Apr. 2024, https://doi.org/10.48084/etasr.7034.

[11] W. Chinkhuntha, A. Owayo and N. Ambassah, "Performance Evaluation of Red Clay Soils stabilized with Bluegum Sawdust Ash and Sisal Fiber as Low-Volume Road Sub-base Materials," *Engineering, Technology & Applied Science Research*, vol. 14, no. 6, pp. 18105–18113 , Dec. 2024, https://doi.org/10.48084/etasr.8772.

[12] M. O. Aboubacar, J. N. Thuo, and O. Alphonse, "Performance Assessment of Coconut Shell Ash as Partial Replacement of Cement in Compressed Earth Blocks," *Seybold Report*, vol. 19, no. 1, pp. 486–498, Apr. 2024.

[13] *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*, ASTM D698-12,

[14] *Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer*, ASTM D854-14, 2023.

[15] *Methods of test for soils for civil engineering purposes - Classification tests and determination of geotechnical properties*, BS 1377-2, 2022.

[16] *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*, ASTM D4318-17e1, 2018/

[17] *Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils*, ASTM D4546-03, 2010.

[18] M. R. P. Rao, M. P. Khambete, and H. N. Lunavat, "Study of rheological properties of psyllium polysaccharide and its evaluation as suspending agent," *International Journal of PharmTech Research*, vol. 3, no. 2, pp. 1191–1197, 2011.

[19] M. A. A.-W. Ali, R. M. Raouf, and M. A. Abdulkarem, "Experimental Assessment of Flaxseed Gel on Mechanical and Physical Properties of Mortar," *International Journal of Nanoelectronics & Materials*, vol. 15, no. 1, 2022.

[20] T. Schanz and Y. Al-Badran, "Swelling pressure characteristics of compacted Chinese Gaomiaozi bentonite GMZ01," *Soils and Foundations*, vol. 54, no. 4, pp. 748–759, Aug. 2014, https://doi.org/10.1016/j.sandf.2014.06.026.

[21] *Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading*, ASTM D2435/D2435-11, 2020.

[22] *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil*, ASTM D2166-06, 2010.

[23] P. Wongsa, P. Phatikulrungsun, and S. Prathumthong, "FT-IR characteristics, phenolic profiles and inhibitory potential against digestive enzymes of 25 herbal infusions," *Scientific Reports*, vol. 12, no. 1, Apr. 2022, Art. no. 6631, https://doi.org/10.1038/s41598-022-10669-z.

[24] Y. Koga, P. Westh, K. Nishikawa, and S. Subramanian, "Is a Methyl Group Always Hydrophobic? Hydrophilicity of Trimethylamine-N-oxide, Tetramethyl Urea and Tetramethylammonium Ion," *The Journal of Physical Chemistry B*, vol. 115, no. 12, pp. 2995–3002, Mar. 2011, https://doi.org/10.1021/jp108347b.

[25] N. Ramamurthy and S. Kannan, "Fourier transform infrared spectroscopic analysis of a plant (Calotropis gigantea Linn) from an industrial village, Cuddalore dt, Tamilnadu, India," *Romanian journal of Biophysics*, vol. 17, no. 4, pp. 269–276, 2007.