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Effect of Pectin Activated by LABSA on Clay Soil Properties

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ABSTRACT: This paper studies the stabilization effect of pectin biopolymer and linear alkyl benzene sulfonic acid (LABSA) on clayey soil. Stabilization of soil by biopolymers has been the focus of several studies, but the use of pectin as a soil stabilizer was scarcely used, let alone the combination of pectin with LABSA. Pectin is a polysaccharide biopolymer that is naturally found in the cell walls of plants. It can bind clay particles, together and increase cohesion between particles. and this binding comes from gel formation behavior that is further activated by acid for the unconfined compressive strength USC test. Hence, the LABSA, which was diluted in distilled water at three concentrations (100/1000, 200/1000, and 300/1000) ml has been added to the soil in the form of liquid-solid with two concentrations (1% and 2%) by weight of dry soil for the unconfined compression test. While Pectin alone in three presents (0.5, 1, 2) % by weight. for other tests. The results showed that the specific gravity, maximum dry density, and optimum moisture content decrease and Atterberg limits increase with the increase in pectin concentration. The UCS increased to 306 kPa at (300/1000 ml, 20-80% solid-liquid). In conclusion, the combined effect of pectin and LABSA could lead to an increase in the compressive strength of clay.

Keywords: Soft clay; stabilization; Pectin; biopolymer; strength.

1. Introduction

Soft soils are prone to fail under load due their low strength high compressibility Therefore, such soils must be improved before construction to avoid building collapse and eliminate or decrease maintenance costs (Al-Neami et al., 2021).

Stabilizing soft clays is essential to improve their strength, reduce compressibility, and enhance load-bearing capacity. Several materials are commonly used to stabilize soft clays, depending on the site conditions and desired outcomes (Bazzazzadegn et al., 2025; Yoobanpot et al., 2017; Fattah et al., 2015; Kadhim et al., 2022; Cong and Lonzhu, 2014).

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Cement is one of the most common stabilizers for soft clays. It reacts with water and soil particles to form a solid matrix that improves strength and reduces plasticity. Portland cement is mixed with the clay, and the amount is typically determined through laboratory testing.

Lime stabilization is effective for clays with high plasticity. Lime reacts with clay minerals and water to form pozzolanic compounds, reducing plasticity and increasing strength. Quicklime or hydrated lime is spread, mixed with the soil, and compacted. Fly ash is a by-product of coal combustion and is often used with lime or cement to stabilize soft clays. It improves soil properties by creating pozzolanic reactions. Mixed into the clay in specific proportions and compacted.

Ground Granulated Blast Furnace Slag (GGBS): Using: GGBS, a by-product of the steel industry, reacts with lime or alkalis in the soil to create cementitious compounds, improving the clay's strength. Often used in combination with lime or cement for enhanced stabilization.

Geopolymers, created from industrial by-products like fly ash, provide eco-friendly stabilization by binding soil particles through chemical reactions. Mixed with soil and cured under controlled conditions. Chemical Stabilizers like Sodium silicate, calcium chloride, or magnesium chloride. These chemicals alter the soil structure and reduce moisture sensitivity, improving the clay's load-bearing properties. They are sprayed or injected into the soil. Bituminous Materials or asphalt stabilizes soft clays by reducing water ingress and improving soil cohesion. Mixed into the clay or used as a surface sealing layer. Polymers and Resins, such as polyurethane or acrylics, bind soil particles and reduce water sensitivity. They are injected into the soil or mixed during stabilization. Fiber Reinforcement (e.g., polypropylene, glass, or coconut fibers) reinforce the clay by improving tensile strength and reducing shrink-swell behavior. They are mixed into the soil in specified proportions.

Geosynthetics like geotextiles, geogrids, and geocells stabilize clays by distributing loads, reducing settlement, and controlling water movement.

Laboratory testing is essential to determine the best stabilizer and dosage for the specific clay type and stabilization goals.

Biopolymer soil stabilization focuses on enhancing natural properties of soil, instead of traditional soil treatment techniques (Idouri et al., 2022), polymeric materials are being used in stabilization of soil because of their availability, danger free, non-toxic and environmentally friendly materials (Nautiyal et al., 2025). Nowadays, polysaccharide biopolymers such as xanthan gum, guar gum, beta glucan, chitosan carboxymethel, lignin, pectin and zein are ongoing used in the field of soil improvement in order to minimize environmental problems. In recent years, biopolymer-based soil treatment (BPST) has been used in geotechnical engineering for a number of purposes, such as erosion control, soil strengthening, and dust management. Even though BPST techniques can guarantee engineering efficacy while satisfying environmental protection standards, BPST technology still needs to be further validated in terms of site suitability, durability, and financial feasibility (Chang et al., 2020).

A variety of chemical treatments, such as adding stabilizers to the soil, are frequently employed to enhance the mechanical properties of soil. The most traditionally utilized additive to soil was Portland cement. Even though Portland cement has been used extensively in various geotechnical engineering procedures, its use to improve soil has been linked to adverse environmental effects and increased carbon dioxide (CO_2) emissions during the cement production process. This is because the cement industry is thought to be accountable for up to 8% of the world's CO_2 emissions each year (Andrew, 2018).

Pectin was chosen for use in the current investigation because it is natural food byproduct with proven benefit in food, pharmacological industries and geotechnical applications. The long term commercial success of pectin has shown the importance of using raw fruit byproducts to produce valuable goods (Chan et al., 2017).

Due to limited previous studies involving the efficacy of pectin as soil stabilizer, this research aims to define the gaps by doing an extensive experiment to show the effect of pectin biopolymer agent activated by sulfonic acid on the soil mechanics. A range of laboratory experiments, including Atterberg limits tests and unconfined compression test for the pectin-treated soil samples were conducted to obtain the engineering performance, soil strength, and plasticity behavior.

The results of this study provide better apprehension of the mechanical behavior of clayey soil treated with pectin for acknowledging and implementation of this biopolymer for geotechnical practices.

2. Materials

2.1. Soil

The soil used in this paper was taken from an area northern of Baghdad city, the soil was a stiff brown silty clay, Standard tests performed to identify physical properties of the soil. Figure 1 shows the grain size distribution results of the soil as following: 4% sand, 41% silt and 55 % clay, according to the Unified Soil Classification System USCS, the soil is classified as CL. Table 1 shows the physical properties of soil used.

2.2. Biopolymer pectin

In recent years, pectin, a naturally occurring polysaccharide, has increasingly attracted attention. Scientists and consumers acknowledge the benefits of natural pectin due to its biodegradability. It is made commercially from citrus peels and apple pomace. Depending on the esterification level, pectin was employed alone or in combination with gelling agents in medicines. Additionally, it is utilized in both commercial and health promotion (Antony et al., 2012) and recently in geotechnical engineering. It has been used as emulsifiers, gelling agents, coating agents, stabilizers, and/or thickeners in food, pharmaceutical, personal care, and polymer products (Chan et al., 2017). It is a polysaccharide with a minor amount of L-arabinose, D-galactose, and L-rhamnose and a high level of galacturonic acid. The galacturonic acid remnant is joined by α-(1–4) links to make a linear chain (Lemboye and Almajed, 2023). As seen in Figure 2, the pectin was utilized in this investigation. The biopolymer's chemical and physical characteristics are shown in Table 2.

There are two types of pectin commercially used: high methylated pectin with a methylation level greater than 50%, and low methylated pectin with a methylation level lower than 50% (Nešić and Seslija, 2016) which is obtained by aminolyzing high methoxy pectin. Hydrophobic forces between methyl groups and hydrogen bonds and low pH conditions facilitates gel formation with high methylated Pectin (Chan et al., 2017) that was used in this study.

2.3. Linear Alkyl Benzene Sulfonic Acid (LABSA)

Linear alkyl benzene (LABSA) was introduced in the sixties as a raw material for cleaning products. Since then, an ongoing and expanding research on its biodegradation and on its environmental and human toxicity has been performed. The efficiency of linear alkyl benzene sulfonate as surfactant is clearly established, and it is one of the safest and most cost-effective products in widespread commercial use (De Almeida, 1994). LABSA is the formal name for the chemical compound sulfonic acid, which is often referred to as dodecyl benzene sulfonic acid. The principle use of this acid is for detergent and cleaning material manufacturing. Its chemical properties are shown in Table 3 while the physical properties are listed in Table 4. LABSA is a viscous acid, to get a uniform and effective concentration, it can be added to distilled water for dilution., LABSA was diluted with following percentages: 100/1000, 200/1000, and 300/1000 ml (Nautiyal et al., 2025) as seen in Figure 3.

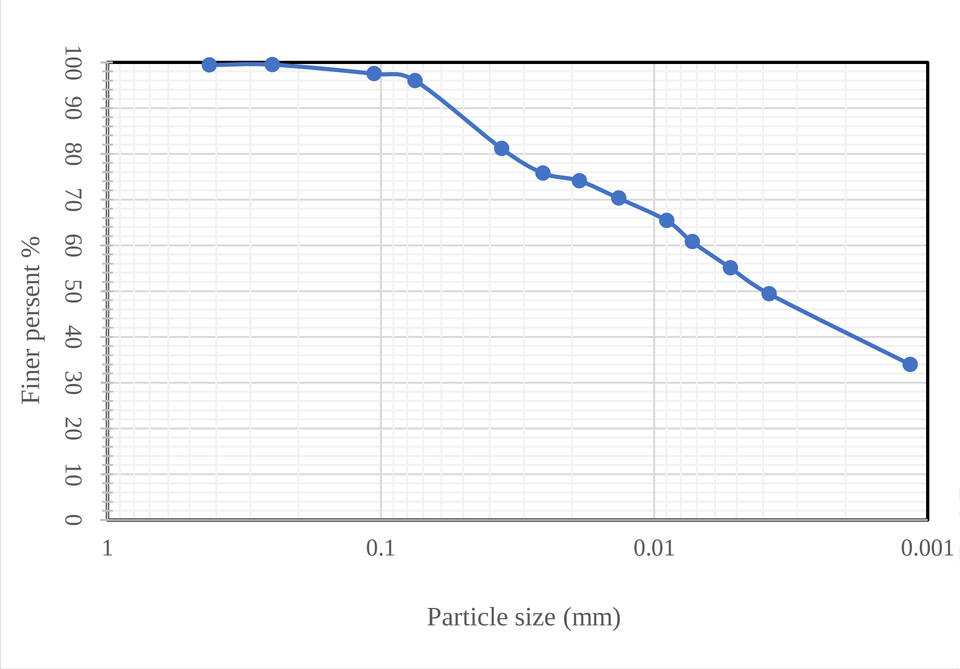


Fig. 1. Grain size distribution.

Table 1. Physical properties of the soil used.

Properties	**Value**	**Standard index**
Liquid limit (LL)%	41	ASTM D4318 [13]
Plastic Limit (PL)%	18	ASTM D4318 [13]
Plasticity Index (PI) %	23	---------
Shrinkage Limit %	12	ASTM D4318 [13]
Activity	0.4	---------
Specific Gravity (Gs)	2.68	ASTM D854 [14]
Gravel %	0	ASTM D422 [15]
Sand %	4	ASTM D422 [15]
Silt %	41	ASTM D422 [15]
Clay %	55	ASTM D422 [15]
Max dry density (g/cm3)	1.65	ASTM D698 [16]
Optimum moisture content %	15	ASTM D698 [16]
USCS classification	CL	--------

Fig. 2. Pectin powder.

Table 2. Properties of the pectin biopolymer.

Mineral	Range
Country of origin	Spain
% of ingredient	40 - 60 %
Lead Pb (ppm)	< 2
Mercury Hg(ppm)	< 1
Mold and Yeast (cfu/g)	< 300
Salmonella (Detection in 25g)	Not Detected
Loss on drying (%)	< 12
Origin	Citrus peel
Appearance	White to beige color powder
Chemical Compositions	
C	37.9
O	53.1
Na	1.1
Mg	2.4
K	0.6
Ca	2.4
Ni	0.9
Cu	1.6
PH value	4.66

Table 3. The chemical composition of LABSA.

Composition	LABSA (wt.%)
Carbon (C)	49.22
Calcium (CaO)	35.94
Oxygen (O)	10.96
Sulfur (SO_3)	1.91
Silica (SiO_2)	1.20
Magnesium (MgO)	0.46
Alumina (Al_2O_3)	0.22
Ferrous (Fe_2O_3)	0.09

Table 4. Physical properties of LABSA as supplied by the supplier.

Item	Property
Color	Dark brown
Chemical formula	C6H4SO3H
Texture	Liquid
Density	1.0485

Fig. 3. Sulfonic acid dilution.

3. Methods

3.1. Specimen Preparation

The soil was oven dried at 110 Co for 24 hours, two concentrations of pectin activated by sulfonic acid to soil mixtures were studied at 1.0%, and 2.0% of dry weight with variable mixing percentages of (additive and activator) (solid/liquid) at which acid was diluted in three concentrations (100/1000,200/1000 and 300/1000 ml), which was used for unconfined compression test, details as in Table 5. While for specific gravity, Atterberg limits and compaction tests we only used pectin in three concentrations (0.5%, 1%, 2%) by dry weight of the soil.

Initially, the biopolymer in powder form was prepared by pouring the powder over the water, while it is quickly stirred, keep stirring until dispersion, as recommended by the manufacturing company not to pour the liquid over the powder. The biopolymer solution is allowed to saturate completely for one day before adding it to the soil. It's sealed with plastic wrap to avoid moisture loss (Ramani and Saisree, 2020). After 24 h, the soil is spread over the pan and the solution is added to the soil and are mixed deeply until a homogenous mixture is formed.

3.2. Testing Program

To understand the effect of biopolymer on soil characteristics, specific gravity, Atterberg limits, compaction tests were performed to the untreated soil and after adding additive at three presents (0.5,1,2)% by weight of dry soil , the unconfined compression test was carried out to the pure compacted soil and after treating with pectin activated by sulfonic acid as most common use of pectin is gelling effect when mixed with sugar and acid (Antony et al., 2012) which acts as binder for soil molecules. Therefore, the polymer was activated it with sulfonic acid at several different mixing ratios.

4. Results and Analysis

4.1. Specific Gravity (GS)

By using Pycnometer (ASTM D 854) [14] to determine the specific gravity of soil. It is represented by mass of a unit volume of soil at a given temperature divided by the mass of the same volume of gas-free distilled water at the same temperature. Test was done on four samples; results are indicated in Figure 4. the specific gravity of the treated soil clearly drops from (2.68) for untreated soil to 2.5 when 2 % biopolymer added Since pectin has a lower density than the mineral components of soil, the overall density of the treated soil decreases, resulting in a lower specific gravity.

The experimental results comprehensively demonstrate the influence of pectin biopolymer, both alone and when activated by LABSA, on the geotechnical properties of the tested clayey soil. The observed changes in physical and strength characteristics can be attributed to the fundamental interactions between the soil particles, the pectin, and the acidic activator.

The reduction in specific gravity with increasing pectin content is a direct consequence of the lower particle density of the organic biopolymer (approximately 1.5-1.7 g/cm³) compared to the native soil minerals (specific gravity of 2.68). As pectin replaces a portion of the denser soil solids, the overall mass per unit volume of solids decreases, leading to a lower specific gravity. This phenomenon is consistent with the incorporation of other low-density organic materials into soil.

Table 5. Details of the experiment matrix.

Experiment matrix for 1% by weight					
Solid-Liquid %	20-80	35-65	50-50	65-35	80-20
Pectin gm	0.284	0.497	0.71	0.923	1.136
Diluted LABSA ml	1.1	0.9	0.7	0.47	0.27
Distilled water ml 100/1000	20.299	20.481	20.663	20.872	21.05
Distilled water ml 200/1000	20.376	20.544	20.712	20.9	21.07
Distilled water ml 300/1000	20.453	20.6	20.761	20.94	21.09
Experiment matrix for 2% by weight					
Solid-Liquid %	20-80	35-65	50-50	65-35	80-20
Pectin gm	0.568	0.994	1.42	1.846	2.2
Diluted LABSA ml	2.2	1.8	1.4	0.9	0.5
Distilled water ml 100/1000	19.298	19.66	20	20.48	20.845
Distilled water ml 200/1000	19.452	19.788	20.124	20.544	20.88
Distilled water ml 300/1000	19.6	19.9	20.22	20.6	20.915

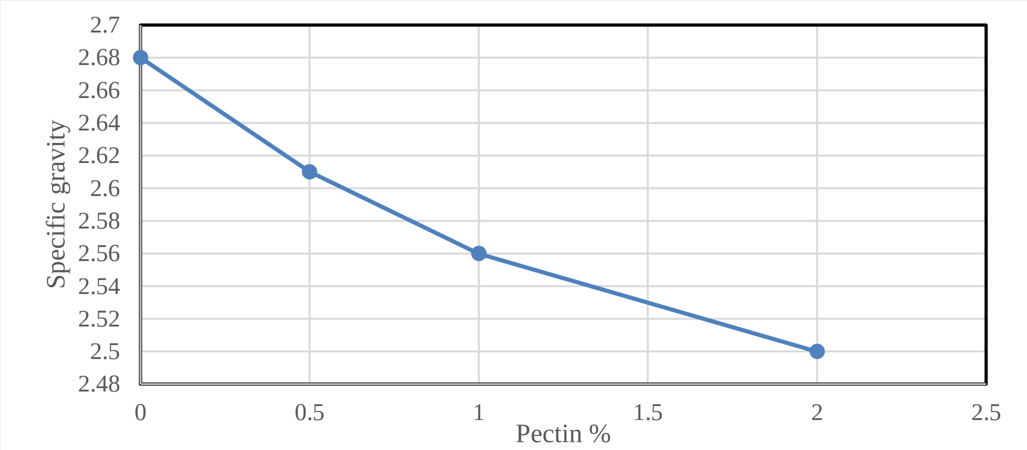


Fig. 4. Specific gravity for the pure soil and soil treated with different biopolymer contents.

4.2 Atterberg Limits

Depending on its moisture level, the soil can be solid, semisolid, plastic, or liquid, and Atterberg limits show the consistency of fine-grained soil. Every state exhibits distinct engineering traits, behavior, and consistency. The liquid limit is important because it shows how quickly the soil may deform when subjected to external force. High liquid limit soils are more ductile and resistant to cracking, whereas low liquid limit soils are often more brittle and prone to breaking. Finding the plastic limit (PL) is just as crucial as figuring out the liquid limit when calculating the soil's plasticity index (PI). The plastic limit is significant because it shows how well the soil can support a load without deforming permanently. Soils with a low plastic limit are generally more compressible and may undergo large deformations under external load; however, the opposite is also true (Ahmed et al. 2024). The tests were done according (ASTM D4318, 2017), four samples were prepared for each test. Table 6 and Figure 5 exhibit the Atterberg limits test results as they show that liquid limit increased after adding biopolymer from 41% to 48% owing to ability of Pectin to increases the cohesion between particles, making the soil more resistant to flow, also the liquid limit values vary depending on the viscosity of pore structure, bonding type and the most importantly flocculation (Bozyigit, et al., 2021).

Besides, the plastic limit increased to 21% due to gel forming behavior of Pectin that surrounds the particles, as a result the plasticity index automatically raises significantly from 23 to 27. These results are in agreement with the results obtained by (Ramani and Saisree, 2020).

The increase in liquid limit (LL: 41% to 48%) and plastic limit (PL: 18% to 21%) suggests enhanced water retention and cohesion due to pectin's gel-forming behavior. The rise in plasticity index (PI: 23 to 27) indicates improved ductility, which is beneficial for reducing soil cracking (Ramani & Saisree, 2020).

The significant alterations in the Atterberg limits—namely the increase in Liquid Limit (LL), Plastic Limit (PL), and consequently the Plasticity Index (PI)—are indicative of a fundamental change in the soil's interaction with water. Pectin, a hydrophilic polysaccharide, possesses a high water-absorption capacity. When mixed with soil, it forms a gel-like matrix that coats the soil particles, increasing the soil's affinity for water and thus raising the moisture content required for the soil to transition between its plastic and liquid states (LL and PL). The resulting increase in PI signifies an enhancement in the soil's cohesive nature and ductility. This improved cohesion can be beneficial for reducing the potential for desiccation cracking in clay soils, as the biopolymer-treated soil can undergo more deformation before fracturing.

The compaction test results are a direct consequence of the biopolymer's influence on the soil's microstructure and workability. The decrease in maximum dry density (γ_{dmax}) and increase in optimum moisture content (OMC) can be explained by several synergistic factors:

- Particle Separation: The viscous pectin gel pushes soil particles apart, acting as a "lubricant" that prevents them from achieving the densest possible packing arrangement under the standard Proctor effort. This disruption of the compaction mechanism leads to a higher void ratio and thus a lower dry density.

- Water Demand: The biopolymer competes with the soil particles for the available water. A significant portion of the added water is absorbed by the pectin for gel formation and is not available to lubricate soil particles for compaction. Therefore, more total water is required to achieve the optimum lubrication effect, resulting in a higher OMC.
- Unit Discrepancy Note: The manuscript states γ_{dmax} dropped from "1.65 gm/cm³ to 1.55 gm/cm³" in one section and from "16.5 kN/m³ to 15.5 kN/m³" in another. While the trend is clear, consistency in units (typically g/cm³ or Mg/m³ for density) is recommended for clarity.

Table 6. Values of Atterberg limits for soil treated with biopolymer**.**

%Polymer	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
0	41	18	23
0.5	42	19	23
1	45	20	25
2	48	21	27

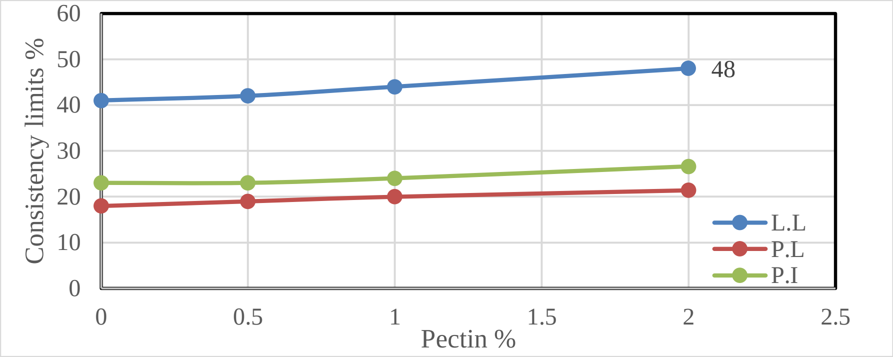


Fig. 5. Effect of biopolymer on the Atterberg limits.

4.3 Compaction Test

Compaction is the process by which soil particles are packed more closely together by dynamic loading; it is achieved through the reduction in air voids with little or no change of water content. In this study, the standard Proctor test was used according to (ASTM D698, 2021). Figure 6 displays the results of the compaction test and the relationship between optimum moisture content and maximum dry unit weight at different polymer contents. At 2% biopolymer, the optimum water content increases from 15% to 17%. this increase because the addition of pectin may reduce the overall compaction efficiency of the soil, making it less dense than untreated clay under the same compaction effort. While the maximum dry density dropped from 1.65 gm/cm³ to 1.55 gm/cm³, pectin enhances the soil's ability to retain water, requiring more moisture for optimum compaction, and high water absorption of the biopolymer (Ahrabi et al., 2000). The low specific gravity of the biopolymer, increased cohesion due to inter-particle bonding, also high-viscosity solutions separate the soil particles leading to compaction mechanism disturbance, these are found to be the underlying reasons for the reduction in maximum dry density. These results agree with the findings of (Ayeldeen et al.,2016), who used guar gum and modified starch for biopolymers-soil mixture, which caused a fall in maximum dry density and a rise in optimum moisture content as biopolymer content increases, and with (Vishweshwaran and Sujatha, 2022), who found that the biopolymer β- Glucan decreases the maximum dry unit weight of high plasticity clayey soil from 15.35 kN/m3 to 14.89 kN/m3 and increases O.M.C from 20 to 26%. The reduction in maximum dry density (1.65 to 1.55 g/cm³) and increase in optimum moisture content (15% to 17%) are consistent with biopolymer-treated soils, where viscous biopolymer solutions disrupt particle packing and increase water demand (Ayeldeen et al., 2016).

The compaction characteristics further support this mechanism. The decrease in maximum dry density and the concurrent increase in optimum moisture content are classic behaviors observed in soils treated with viscous biopolymers. The pectin gel introduces a cohesive, viscous medium that hinders the densest possible packing of soil particles under a given compaction effort. Furthermore, the biopolymer's demand for water to form its gel structure increases the total amount of water needed to lubricate the particles for optimal compaction, explaining the rise in optimum moisture content. This suggests that field compaction of pectin-treated soils may require adjusted moisture control and potentially higher compactive effort to achieve target densities.

4.4 Unconfined Compression Strength

The unconfined compression test is used to determine the shear strength of the soil. The test was done on a cylindrical specimen with 76 mm in height and 38 mm in diameter. Vertical compression was applied to the sample until failure occurred which was noted along the diagonal plane (Majeed and Taha, 2015). Split mold was used to compact the sample in three equal layers which was given blows into the required grades by using a steel tamping rod weight (300 gm), (37.5 mm bottom and 1.5 mm top) in diameter and 8 mm in thickness. Thirty samples were prepared as indicated and conducted with trial mixing percentages, the optimum water content was adopted, subtracting the amount of water previously used to dilute the LABSA, since the density of acid (1.0485 g/cm3) is near to the density of water (Vassilevet et al., 2020). The experimental matrix of performed tests was executed using two additive concentrations and three dilution ratios (100/1000, 200/1000 and 300/1000) ml, cured for three days at room temperature.

Table 7 and Figures 7 to 9 show the results of the UCS tests based on the indicated dilution ratios used for each solid/liquid blend proportion. An increase in UCS was noticed in all additive concentrations and mixing ratios (solid/liquid) in comparison to untreated soil, this increase may be due to gel forming behavior of pectin (Muhauwiss et al., 2024), which is activated by low pH solute (Narasimman, 2016), in this study the low pH solute we used is LABSA. Also, LABSA can cause dispersion of the clay particles by reducing their surface charge and causing the particles to separate and potentially make the soil more likely to binding with pectin. The use of sulfonic reduces capillary ascending and permeability (Abu-Zreig and Rudra, 2003). Hence, the highest compressive strength achieved was 306 kPa at 1% of (300/1000 ml) and mixing ratio (20-80%) as in Figure 10, and 244.5 kPa at 2% of (300/1000 ml) mixing ratio (35-65%). As noticed for a dilution ratio of (100/1000) ml and (200/1000) ml, the UCS results were lower than that of (300/1000) ml which could be attributed to the low concentration of diluted acid. These results supports the findings of (Bozyigit et al., 2021), as the Cu increases with biopolymer concentration and curing time for all biopolymers studied.

The most pronounced effect was observed in the unconfined compressive strength (UCS), where the synergistic action of pectin and LABSA led to substantial improvements. The key mechanism here is the acid-activated gelation of high-methylated pectin. LABSA, being a strong acid, provides the low-pH environment necessary to promote the formation of a firm, three-dimensional pectin gel network. This gel acts as a robust binding agent, cementing the clay particles together and filling the pore spaces, which significantly enhances the soil's shear strength. The surfactant nature of LABSA may also contribute by dispersing clay aggregates, thereby increasing the surface area available for pectin bonding.

The test results reveal a critical insight into the optimization of the mixture. The highest UCS of 306 kPa was achieved not with the highest pectin content, but with a moderate 1% pectin combined with the highest LABSA concentration (300/1000 ml) at a high liquid content (20-80 solid-liquid ratio). This suggests that the activation process by the acid is more crucial for strength development than simply adding more biopolymer. At a 2% pectin content, the strength gains were generally lower, which could be attributed to the formation of an excessive, potentially weaker biopolymer matrix that disrupts the intimate soil-to-soil contacts, or due to difficulties in achieving proper compaction as indicated by the standard Proctor results. This non-linear relationship underscores the importance of identifying an optimal dosage that balances binding capacity with soil structure integrity.

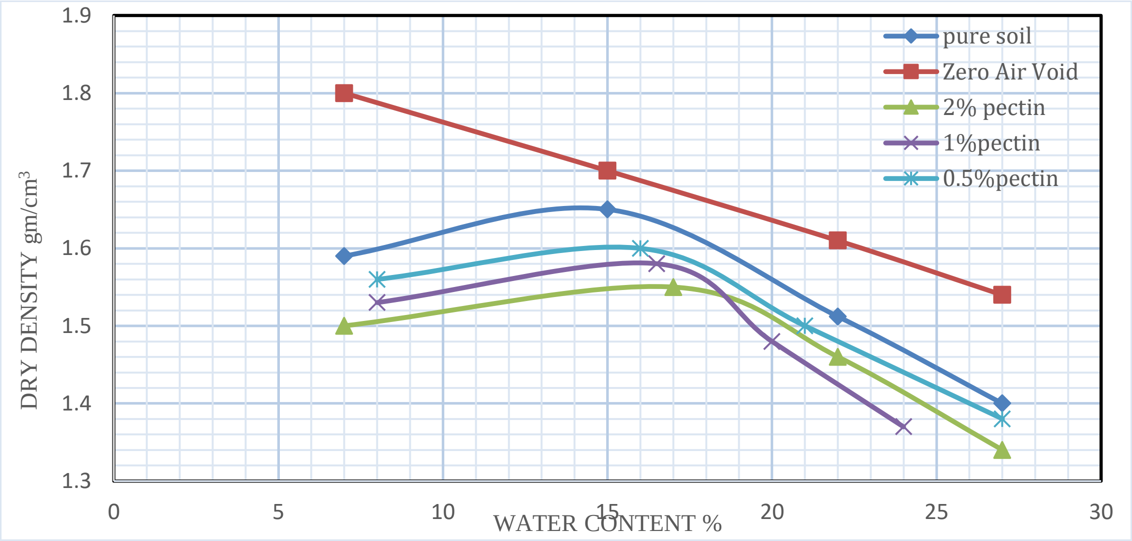
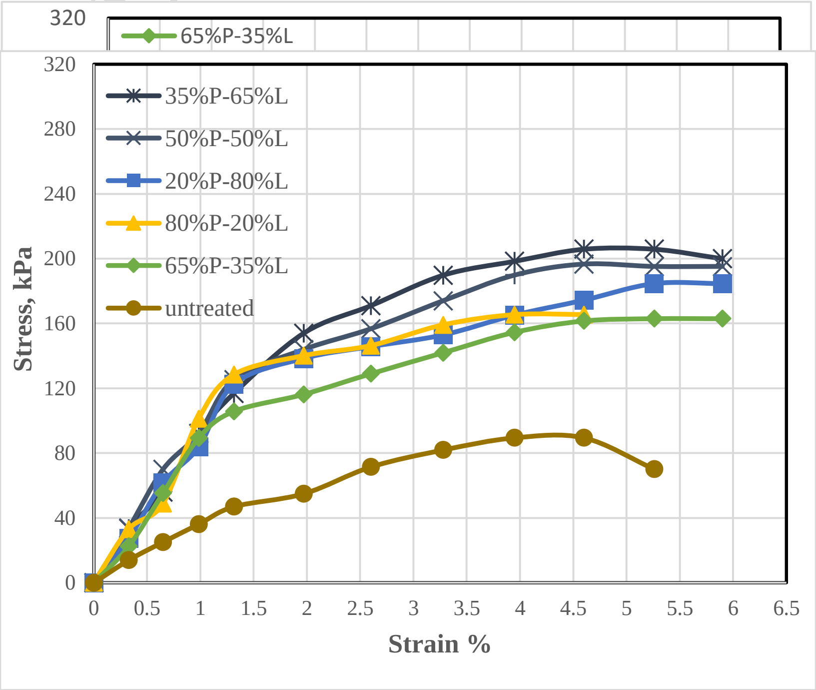


Fig. 6. Compaction curves with different bio-polymer contents.

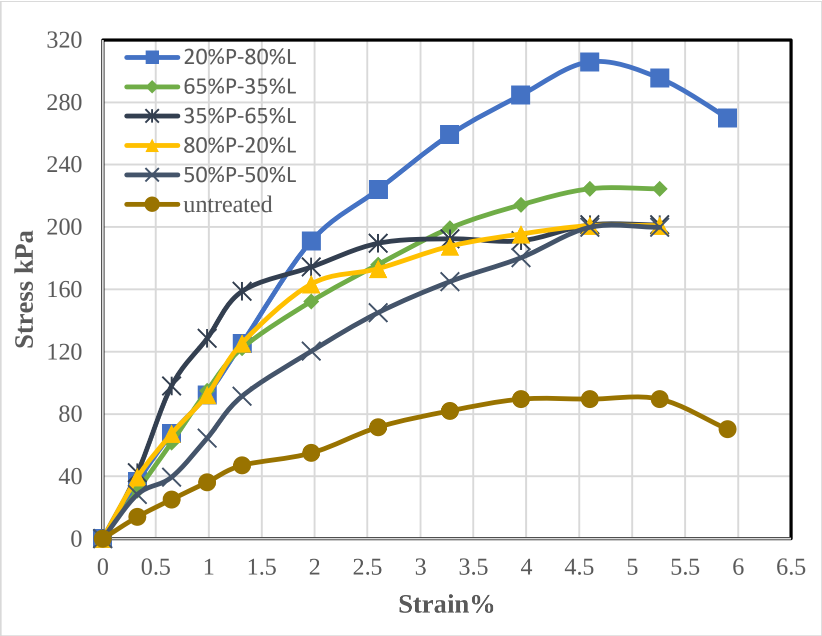
Table 7. UCS Values (kPa).

	Mixing ratio %				
	Percentage of additive = 1% of dry weight				
Dilution ratio (ml)	**20-80**	**35-65**	**50-50**	**65-35**	**80-20**
100/1000	164.9	162.3	158.3	175	158.4
200/1000	184.5	205.84	195.15	163	165.4
300/1000	306	201.4	199.8	224.5	200.8
	Percentage of additive = 2% of dry weight				
100/1000	125.3	168	158.6	142.2	149.15
200/1000	132.6	172	158.6	149.2	142.2
300/1000	158.3	244.5	167.3	169.6	191.7

(a) 100/1000 ml

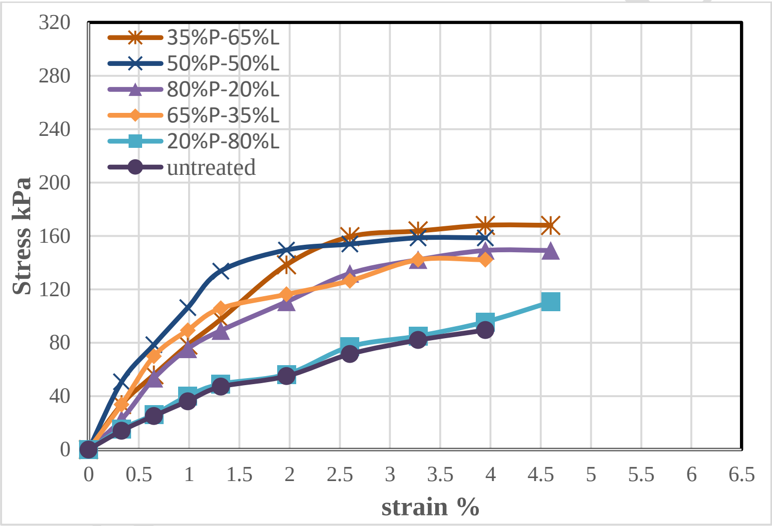


(b) 200/1000 ml

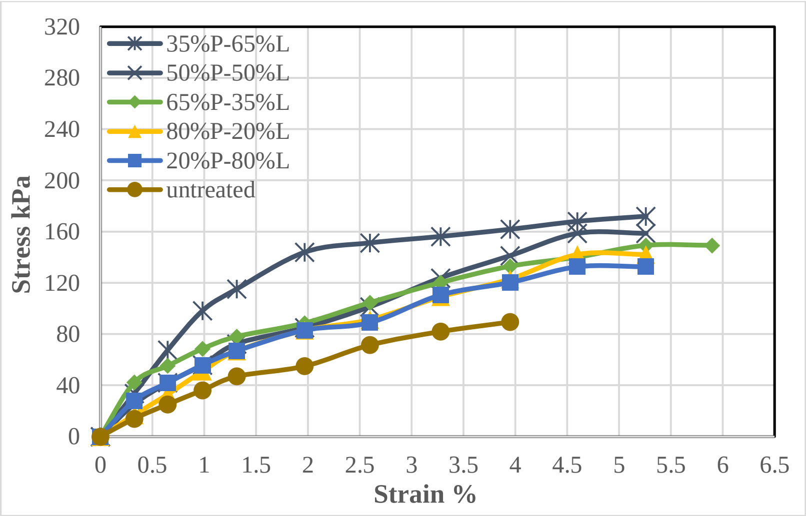


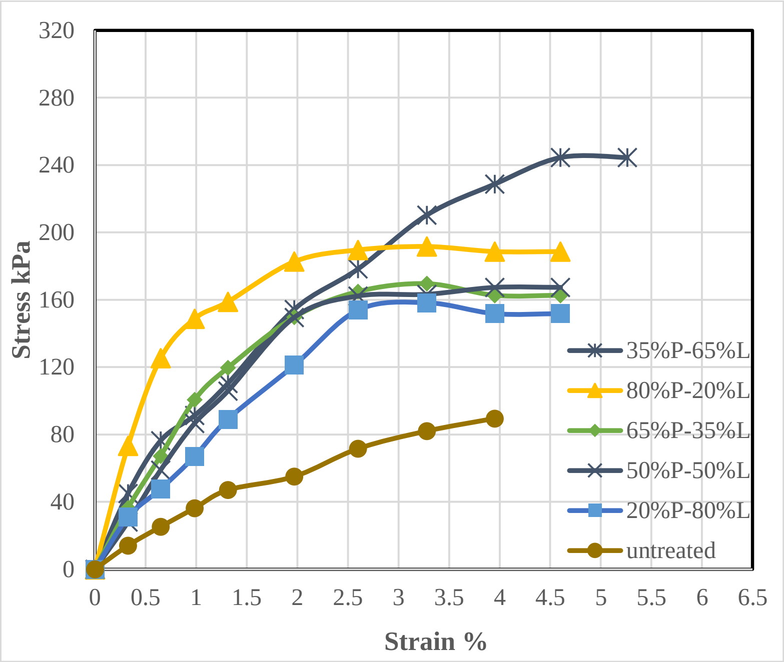
(c) 300/1000 ml

Fig. 7. The stress-strain curves of soils treated with different dilution ratios of 1% additive.

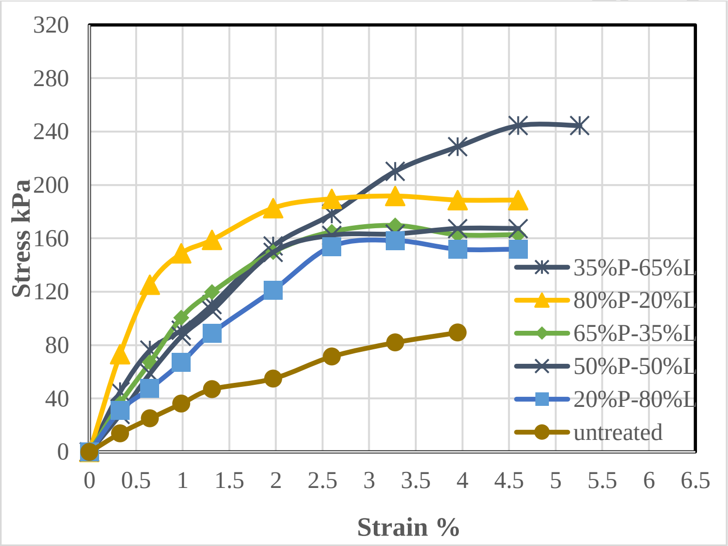


(a) 100/1000 ml



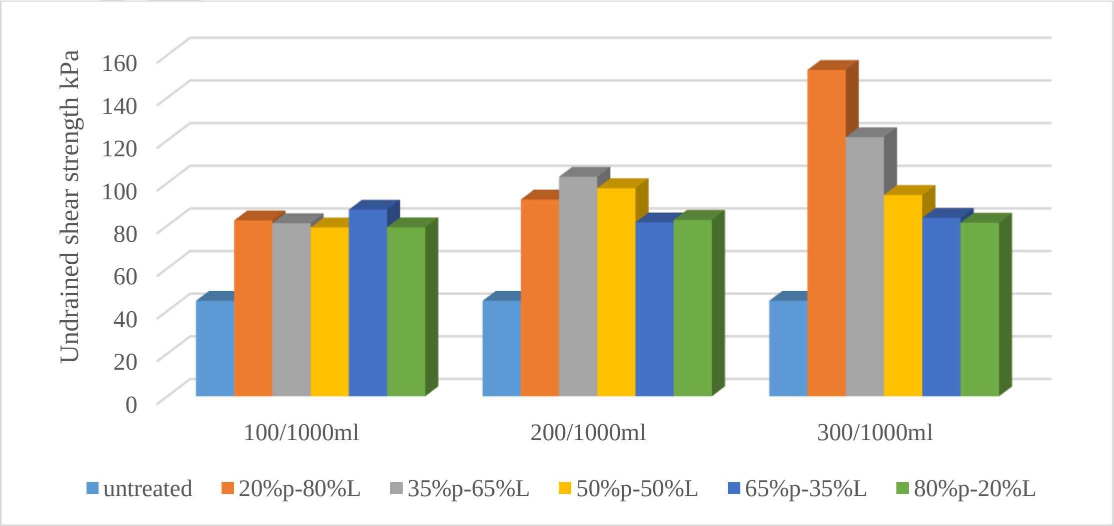


(b) 200/1000 ml

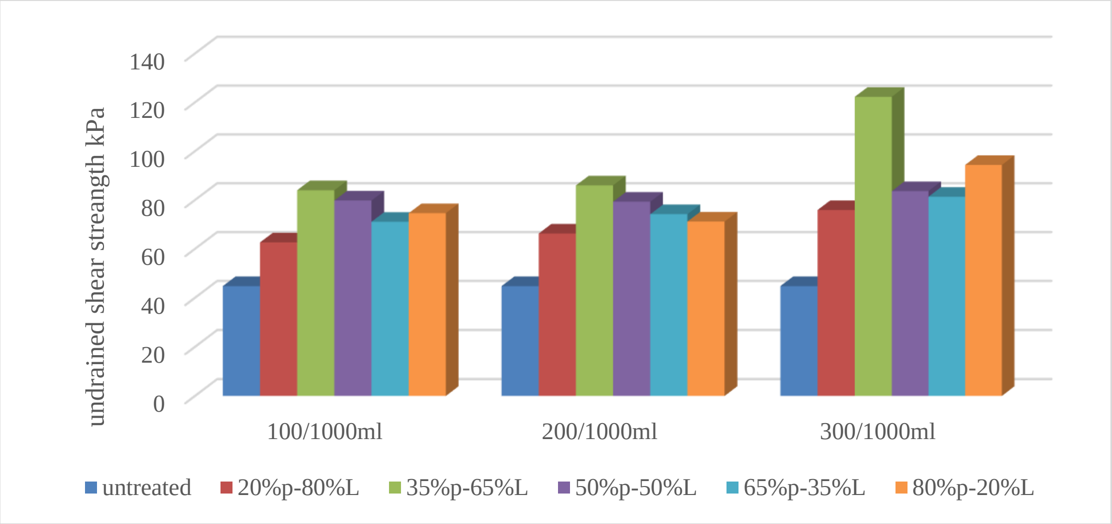


(c) 300/1000 ml

Figure 8. The stress-strain curves of soils treated with different dilution ratios of 2% additive.



(a) 1%.



(b) 2%

Fig. 9. Undrained shear strength values for soils treated with different additives percentages.

(a) (b) (c)

Fig. 10. (a-c) UCS device, (b) untreated soil, (c) treated soil.

The unconfined compressive strength (UCS) increased significantly (up to 306 kPa at 1% pectin + 300/1000 LABSA), highlighting the role of LABSA in activating pectin's binding capacity. Possible mechanisms include:

- Gel Formation: Pectin's gelation, enhanced by LABSA's acidic pH, creates a stable matrix that binds soil particles (Narasimman, 2016).
- Particle Dispersion: LABSA's surfactant properties may disperse clay aggregates, allowing pectin to coat particles more effectively (Abu-Zreig et al., 2003).
- Optimal Dosage: The highest UCS was achieved at low pectin (1%) but high LABSA (300/1000 ml), suggesting that excessive pectin (2%) may hinder compaction, while LABSA's acidity is critical for activation.

In summary, the treatment transforms the soil from a particulate system to a composite material where the strength is governed by the biopolymer matrix. The pectin-LABSA combination effectively creates an in-situ bio-cementation within the soil fabric, offering a promising, environmentally friendly alternative to traditional chemical stabilizers. However, the trade-offs, such as reduced density and increased water demand, must be carefully considered in design applications. Future work should investigate the long-term durability of this stabilization under wet-dry cycles and its performance under different loading conditions.

The most significant finding of this study is the dramatic improvement in **Unconfined Compressive Strength (UCS)** when pectin is activated by LABSA. This is not a simple additive effect but a synergistic activation where LABSA unlocks the binding potential of pectin.

- **Acid-Activated Gelation:** High-methylated pectin (HMP), used in this study, forms gels primarily in low-pH, high-sugar environments. In this application, LABSA provides the crucial acidic conditions (low pH). In an acidic medium, the electrostatic repulsion between the negatively charged pectin chains is reduced, allowing the polymer chains to associate and form stronger, more rigid gels through hydrogen bonding and hydrophobic interactions. This robust gel acts as a "glue," binding soil particles together at their points of contact and creating a cemented soil structure.
- **Surfactant-Induced** Dispersion: LABSA, as a surfactant, can adsorb onto the surfaces of clay particles. This adsorption can neutralize some of the negative charges on the clay surfaces, reducing inter-particle repulsion and causing flocculation, or it can help disperse clay aggregates, increasing the surface area available for pectin coating. Both mechanisms can lead to a more homogeneous and stronger soil-biopolymer matrix.
- Optimum Dosage and the Solid-Liquid Ratio: The results reveal a critical optimization landscape. The highest UCS (306 kPa) was achieved with a moderate pectin content (1%) but a high LABSA concentration (300/1000 ml) and a high liquid content (20-80 solid-liquid ratio). This combination suggests that:
  - Sufficient Activator is Key: A high concentration of LABSA ensures the pH is low enough to fully activate the gelation process.
  - Adequate Fluid Medium is Necessary: A high liquid ratio provides the necessary medium for the pectin to fully hydrate and disperse, allowing the gel network to develop uniformly throughout the soil sample.
  - More Biopolymer is Not Always Better: At 2% pectin, the strength was generally lower. This suggests that an over-abundance of biopolymer may create thick, localized gel pockets that prevent intimate soil-to-soil contact and act as weak planes, or it may hinder compaction to a greater degree, resulting in a less dense and therefore weaker specimen.

In conclusion, the treatment fundamentally transforms the soil from a frictional-cohesive particulate system into a composite material where strength is governed by a continuous, acid-activated biopolymer matrix. The pectin-LABSA system creates an in-situ bio-cementation, offering a promising sustainable alternative. However, the trade-offs—such as reduced density, increased water demand for compaction, and the non-linear dosage response—must be meticulously balanced for successful field application. Future research should focus on the long-term durability of this stabilization under environmental cycles (wetting-drying, freezing-thawing) and its performance under sustained and dynamic loading.

5. Conclusions

In this study, a trial was made to answer the question of how much pectin affect the soil properties and how much pectin activated by sulfonic acid affect shear strength parameters. The following conclusions could be obtained:

1- Pectin, as an eco-friendly biopolymer, offers a sustainable alternative to traditional soil stabilizers like cement and lime.

2- The measurements of soil treated with pectin at three present (0.5,1,2) % publish that the Specific gravity decreased by about 7% as biopolymer content increased, while liquid Limit, and plastic limit increased by about 17%, subsequently plasticity index increased.

3- Adding the biopolymer dropped the maximum dry density from 16.5 kN/m3 to 15.5 kN/m3 and slightly increased the optimum moisture content from 15 % to 17%.

4- Adding biopolymer activated with LABSA that showed significant improvement at all percentages and mixing ratios compared to untreated soil for which the highest compressive strength of 306 kPa, obtained at a volume ratio of (300/1000) ml and a mixing ratio of (20-80) (solid- Liquid) % at 1% additive.

This study confirms that pectin-LABSA composites enhance clay soil strength and plasticity while reducing environmental impact. Future research should focus on durability, scalability, and economic feasibility to advance biopolymer-based soil stabilization.

Conflict of Interest

The authors declare no conflict of interest and didn't receive any funding in this study.

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