Evaluation of the Shear Strength of Clayey Sand Treated with Lignin Biopolymer

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Evaluation of the Shear Strength of Clayey Sand Treated with Lignin Biopolymer

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Abstract: *This study evaluated lignin biopolymer (LIG) as a sustainable soil stabilization technique for Zamboanga ultisol, a clayey sand prevalent in the Philippines prone to instability from moisture changes. Triaxial compression tests (UU and CU) were conducted on samples with 0%, 2.5%, 5%, and 10% LIG under confining pressures of 100, 200, and 300 kPa. UU test results were variable, but 2.5% LIG showed potential for improving undrained shear strength, particularly at 300 kPa. CU tests revealed that 2.5% LIG significantly increased effective cohesion while decreasing the effective angle of internal friction. The findings suggest that LIG, especially at 2.5% concentration, can effectively enhance the shear strength parameters of clayey sand*

Keywords: lignin biopolymer, soil stabilization, shear strength, ultisols, triaxial test

1. INTRODUCTION

Soil stability is a key consideration in geotechnical engineering, given the direct influence of the physical and mechanical properties of the underlying soil on the safety, functionality, and longevity of structures built upon the ground [1]. One major factor affecting soil stability deals with shrink-swell behavior and volumetric fluctuations in soil. Ultisols are clayey sands that exhibit pronounced shrink-swell characteristics in response to changes in moisture levels. Commonly found in lowland and upland areas, ultisols are typically composed of clayey sands and are characterized by their loose to medium consistency, reddish hue, and acidic pH (below 5). These soils undergo considerable volume changes during cycles of wetting and drying, leading to compromised stability and structural failure over time [2].

Moisture sensitivity and pore pressure effects further contribute to instability, especially in clayey sands. These soils are highly responsive to changes in moisture content, which can result in ground expansion or settlement. In regions susceptible to frequent flooding, such as the Philippines, intense rainfall can cause a sudden rise in pore water pressure [3]. This increase reduces soil shear strength and may ultimately trigger landslides or other forms of ground failure [4].

These characteristics require effective stabilization strategies to mitigate plasticity, reduce permeability, and improve overall strength. While traditional stabilizers like lime and cement are commonly used, their environmental implications have led to growing interest in eco-friendly alternatives. Conventional soil stabilization approaches typically employ mechanical compaction or chemical additives such as lime and Portland cement [5]. While effective in enhancing soil strength and reducing void ratios, mechanical methods are energy-intensive, and chemical stabilizers are associated with substantial carbon dioxide emissions, primarily due to cement production [6], [7]. Moreover, reliance on pozzolanic reactions can lead to brittle behavior under dynamic loading conditions, such as earthquakes, posing limitations in seismically active areas.

Considering these environmental and performance limitations, there is growing interest in biopolymers as sustainable alternatives for soil stabilization [5]. These naturally derived, biodegradable materials have been increasingly explored in geotechnical applications due to their rheological control, water retention capabilities, and adhesive properties, thus offering ecological advantages and functional performance in soil reinforcement [8]. Among these, lignin (LIG), a complex aromatic polymer found abundantly in plant cell walls [9], [10], has demonstrated potential in construction materials due to its adhesive and hydrophobic properties [11]. In clay-rich soils, lignin can reduce moisture infiltration, mitigate swelling and shrinkage, and improve resistance to shear deformation. Compared to other predominantly hydrophilic biopolymers such as xanthan gum, agar gum, or chitosan, lignin's water-repellent character makes it especially suitable for stabilizing clayey soils under fluctuating moisture conditions [12]. Its irregular aromatic structure, composed of phenolic sub-units, confers greater durability than cellulose-based polymers, which are more susceptible to biodegradation over time [13]. Past studies have shown lignin to enhance both unconfined compressive strength (UCS) and cohesion, making it a promising candidate for soil improvement [4], [14].

To evaluate soil strength improvement, this study used triaxial tests—unconsolidated undrained (UU) and consolidated undrained (CU)—to obtain key parameters like cohesion, internal friction angle, and pore pressure. UU tests assess short-term strength without drainage, while CU tests provide a fuller picture after consolidation. Building on previous findings, this study explores the effectiveness of coconut-derived lignin in stabilizing Zamboanga Ultisol, using triaxial testing to evaluate its potential as a sustainable, locally sourced soil stabilizer.

2. MATERIALS

This study evaluated the influence of lignin biopolymer (LIG) on the shear strength characteristics of Zamboanga Ultisol, a clayey sand prevalent in the Philippines. The research involved systematic sample preparation and laboratory testing using standard triaxial procedures to determine the effects of lignin treatment under varying confining pressures.

2.1 Soil

The test material was Zamboanga Ultisol, collected from upland areas in Zamboanga del Norte, located at the island of Mindanao in the Philippines. Consistent with typical Ultisols found in the country, the soil is reddish in color, acidic (pH < 5), and exhibits a medium to loose consistency with a high clay content [15], [16].

2.2 Lignin Biopolymer

An initial attempt was made to extract the lignin from coconut husk. The husks were crushed to a mesh size of 40–60 and drying at 60°C for at least 16 hours. Reagents used for extraction included a 30% hydrogen peroxide solution, sulfuric acid, and sodium hydroxide. The lignin isolation process used an alkaline hydrogen peroxide solution, which involved adding 20 grams of coconut husk into a 500 ml flask with 180 mL of demineralized water containing 1.5% H_2O_2 (with a volume/weight ratio of 9:1). A 2N NaOH solution was added to the mixture until a pH of 11 was achieved. The mixture was then isolated using a heating oil bath at 100°C for 3 hours after reaching temperature. Following isolation, the liquid phase was separated from solids using filter paper. Lignin was precipitated by adding 2N H_2SO_4 until the pH became 2, followed by stirring the liquor for 4 hours. The precipitated lignin was dried at 60°C for 6 hours.

To validate the purity of the extracted lignin, a FTIR spectrometer was used to analyze its spectral fingerprint. However, the yield of the extracted lignin was low. The study proceeded with commercially available lignin. The chemical identity of both extracted and purchased lignin was verified via Fourier-transform infrared spectroscopy (FTIR), confirming spectral conformity with lignin standards [17].

Significant similarities were found between the spectral profiles for pure and extracted lignin, with peaks corresponding to key functional groups like hydroxyl, methoxy groups, and aromatic ring vibrations present in both spectra. While there were differences in specific peak values, these were attributed to the variation in the source material (coconut husk versus corn husk in the referenced standard). The presence of the key functional group peaks confirmed that lignin was successfully extracted.

The FT-IR spectrum of the purchased lignin showed high similarity in both values and graphical representation when compared to the pure lignin spectrum. This close match indicated a high level of purity and consistency in the purchased lignin, confirming its reliability as a viable alternative for the study.

2.3 Lignin Concentrations

The study utilized three concentrations of lignin biopolymer (LIG) as an additive to the clayey sand. These concentrations were 2.5%, 5%, and 10%. Untreated clayey sand (0% LIG) was also included for comparison. These specific percentages (2.5%, 5%, and 10%) were based on Canakci et al. [14] to compare and obtain the most beneficial impact of LIG on clayey sand using these concentrations.

These concentrations were used in the Unconsolidated Undrained (UU) triaxial tests for all four variations (0%, 2.5%, 5%, and 10%). For the Consolidated Undrained (CU) triaxial tests, only the untreated soil (0%) and the soil treated with 2.5% LIG were tested. The decision to further investigate the 2.5% concentration with CU testing was based on the Unconsolidated Undrained test data which showed potential in terms of higher results compared to the other treated samples.

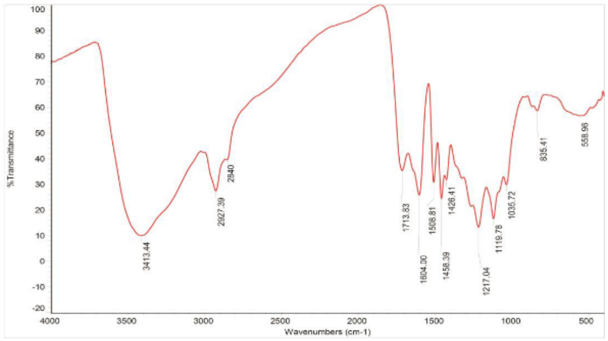


Fig. 1. FTIR spectra of pure lignin [17]

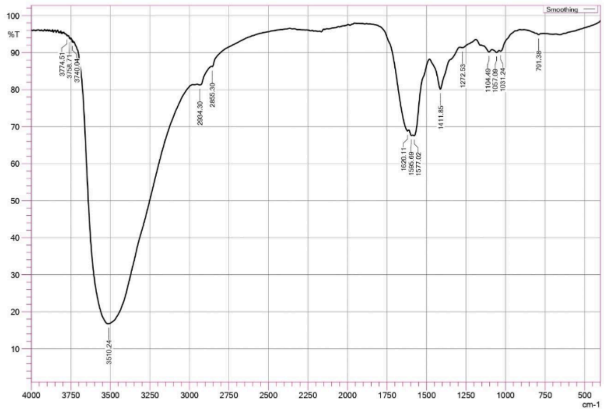


Fig. 2. FT-IR spectra of extracted lignin

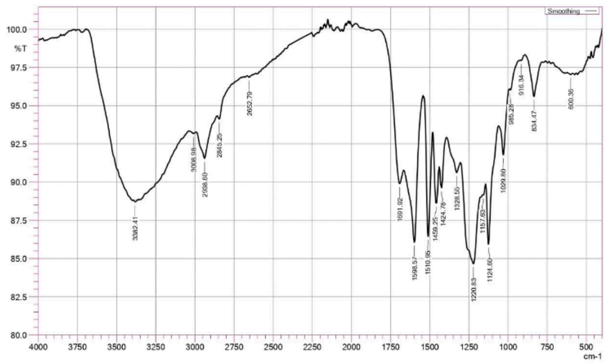


Fig. 3. FT-IR spectra of purchased lignin

2.4 Water

For the soil samples treated with lignin biopolymer (LIG), water was mixed at optimum moisture percentage, which was determined to be 36.64% for the untreated ultisol sample [16]. Meanwhile, de-aired water was used throughout all triaxial test trials to eliminate entrapped gases that could influence pore pressure behavior during testing.

3. METHODOLOGY

3.1 Sample Preparation

The collected soil was oven-dried to remove moisture and then sieved through a 2.36 mm mesh. The liquid lignin solution was diluted with water (LIG:water = 0.59:0.51) to reach the desired moisture content. The diluted LIG solution was then uniformly mixed onto the dried soil specimen using a pan and spatula until a homogeneous mixture was obtained. The solution was stored in sealed, air-tight containers at room temperature for 24 hours to allow for proper curing and interaction between soil and lignin, and to prevent aggregation of particles. Three specific concentrations of LIG were used: 2.5%, 5%, and 10% by volume/weight ratio based on the soil, following parameters determined by Canakci et al. [14].

Specimens were prepared using the moist tamping method in a split cylindrical mold (36 mm diameter × 72 mm height), compacted in five layers, each tamped ten times, to achieve a target Relative Density (D_r) of 50%. This density represents an equilibrium state between shear strength and compressibility in granular soils, providing a conservative estimate suitable for analyzing soil stability. Once the required layers and tamps were completed, excess soil at the top and bottom of the split mold was scraped off using a spatula to ensure an even and flat cylindrical shape. The diameter, height, and weight of the prepared specimens were then measured for computations and to ensure replicability.

3.2 Triaxial Testing

The shear strength behavior was assessed using Unconsolidated Undrained (UU) and Consolidated Undrained (CU) triaxial compression tests in accordance with ASTM D4767 [18] and ASTM D2850 [19] for partially saturated soils.

The UU tests began with the application of an isotropic confining pressure (CP), which was applied quickly to prevent settlement or consolidation of the soil sample. Three specific confining pressures were used: 100 kPa, 200 kPa, and 300 kPa. During this initial compression phase, drainage of pore water was prevented. Following the application of the confining pressure, the shearing stage commenced. In this phase, the confining pressure was kept constant, while axial stress was applied incrementally to the sample. Throughout the shearing phase, the drainage of pore water was still prevented. The axial stress was increased at a consistent rate of 1% axial strain per minute. A total of 18 UU tests were conducted: two trials for the 0% and 2.5% LIG concentrations at each of the three confining pressures, and one trial for the 5% and 10% LIG concentrations at each confining pressure. For the CU tests, only samples of untreated soil (0% LIG) and soil treated with 2.5% LIG were tested, based on results from preliminary UU tests. The CU test consists of three main phases: Saturation, Consolidation, and Shearing. First, during the saturation phase, the objective was to fill "all the voids within the sample with water", performed slowly to increase pressure and remove water, assuming the use of de-aired water at room temperature. Next, in the consolidation phase, specific confining pressures (CP) of 100 kPa, 200 kPa, and 300 kPa were applied incrementally to the saturated samples. During this phase, drainage was allowed, continuing for 24 hours or until volume and porewater pressure changes became constant. Finally, the shearing phase commenced with the confining pressure kept constant, and axial stress was applied to the sample. Crucially, drainage was not allowed during this shearing stage. The axial stress was increased at a consistent rate of 1% axial strain per minute during shearing. A total of six CU tests were conducted, with one trial for each of the two LIG concentrations (0% and 2.5%) at each of the three confining pressures.

3.3 Data Analysis

Axial stress was plotted against axial strain for all tests to analyze the soil's behavior during shearing. These curves helped identify strain hardening (ductile failure) or strain softening (brittle failure) modes. Mohr's circles were plotted for the untreated and LIG-treated samples under different confining pressures (100 kPa, 200 kPa, and 300 kPa). These circles illustrate the shear strength of the soil against normal stresses. For CU tests, effective stress Mohr's circles were plotted, accounting for pore water pressures

Shear strength parameters were calculated from the Mohr's circles obtained from the UU tests. The undrained shear strength used is:

$$S_u = c = \frac{(\sigma_1 - \sigma_3)}{2} = \frac{\sigma_d}{2} \#(1)$$

Cohesion and angle of internal friction were determined from the effective stress failure envelope plotted from the effective stress Mohr's circles in CU tests. These parameters were compared with typical values for clayey sands.

For the CU tests, pore water pressure was plotted against axial strain. The behavior of pore water pressure during shearing (compression) was observed to correspond with the strain-softening (ductile failure) seen in the stress-strain curves.

Stress paths were plotted using the deviator stress (q) on the vertical axis and the mean effective stress (p') on the horizontal axis. These graphs, based on CU test data, provided insights into stress-strain behavior and loading history of the soil. The formulas used for calculation were

Stress paths were plotted using the deviator stress (q) on the vertical axis and the mean effective stress (p') on the horizontal axis. These graphs, based on CU test data, provided insights into stress-strain behavior and loading history of the soil. The formulas used for calculation were:

$$q = \frac{(\sigma_1 - \sigma_3)}{2} \#(2)$$

$$p' = \frac{(\sigma_1' - \sigma_3')}{2} \#(3)$$

The excess porewater pressure coefficient (A_f) was calculated using the porewater pressure at failure and the deviator stress at failure to determine the type of clay (e.g., lightly overconsolidated). An A_f value below 1 indicates the sample was slightly overconsolidated prior to undrained compression.

3.4 Validation of Findings

The mechanical performance of the LIG-treated soil was compared to criteria outlined in Department Order No. 54 of the Philippine Department of Public Works and Highways (DPWH), specifically Section 206.2.1

and 206.2.2 [20], which focused on the applicability of stabilized subbase, base, or surface course in road construction. The analysis checked if the treated soil met requirements for material durability, quality, and environmental safety

4. DISCUSSION OF RESULTS

This section presents the key findings of the experimental investigation on the influence of lignin biopolymer (LIG) on the shear strength characteristics of Zamboanga Ultisol. The results were organized based on Unconsolidated Undrained (UU) and Consolidated Undrained (CU) tests with particular emphasis on how LIG concentration and confining pressure influenced soil behavior.

4.1 Unconsolidated Undrained (UU) Triaxial Test

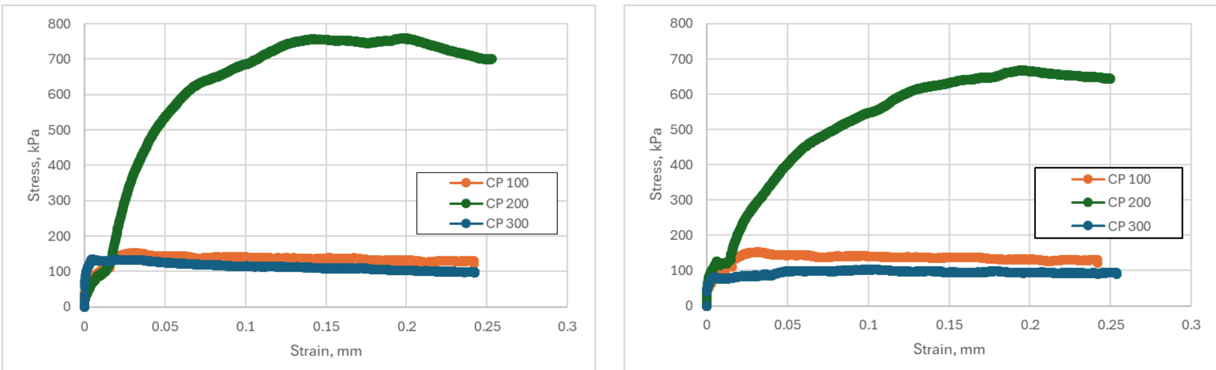
The UU triaxial tests demonstrated variability in undrained shear strength across specimens despite maintaining a consistent relative density (D_r = 50%) and no volume change, which is characteristic of this test type. Results are shown in Table 1. The observed inconsistencies, ranging from 30.04% to 147.69% variation, were attributed to sample preparation challenges associated with the moist tamping technique, which made it difficult to reproduce identical sample arrangements.

For untreated soil, the stress-strain response varied with confining pressure (CP) as shown in Fig. 4. At 100 kPa, the soil exhibited strain hardening followed by brittle failure, while at 200 and 300 kPa, the behavior shifted to ductile failure with strain softening sustained through 15% axial strain. Notably, a higher deviator stress at failure was recorded at 200 kPa than at 300 kPa, suggesting anomalous behavior potentially linked to particle arrangement or fabric effects.

LIG-treated specimens (2.5%, 5%, and 10%) generally displayed strain softening behavior at all CP levels, indicating ductile failure and improved load-bearing performance. The deviator stress at failure increased with confining pressure, with the 2.5% LIG treatment yielding the highest undrained shear strength at 300 kPa as illustrated in Fig. 5. While improvements were observed at lower CP (100 kPa), the enhancement at higher CP was inconsistent across trials, particularly for 5% and 10% LIG samples as shown in Fig. 6. This suggests that higher LIG content may diminish inter-particle friction, potentially due to a lubricating effect caused by excessive biopolymer coating. This suggests that while lignin can significantly enhance soil properties, there is an optimal concentration, with 2.5% being the most effective for clayey sand in this study.

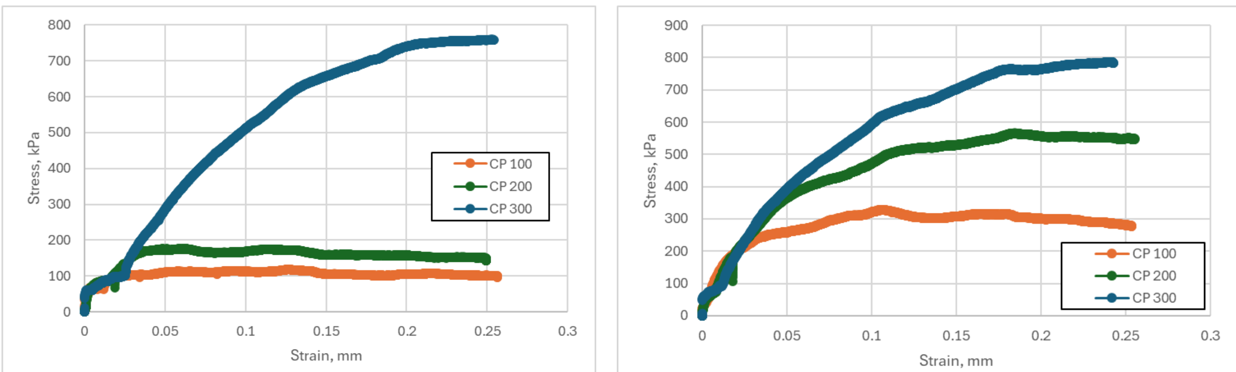
Table 1. Summary of Undrained Shear Strength for UU Test

Confining Pressure	0% LIG Trial 1	0% LIG Trial 1	2.5% LIG Trial 1	2.5% LIG Trial 2	5% LIG	10% LIG
100 kPa	76.21 kPa	76.21 kPa	52.62 kPa	153.68 kPa	40.01 kPa	28.47 kPa
200 kPa	316.10 kPa	377.33 kPa	87.96 kPa	264.32 kPa	81.28 kPa	211.11 kPa
300 kPa	47.48 kPa	54.71 kPa	328.43 kPa	350.79 kPa	287.82 kPa	222.98 kPa



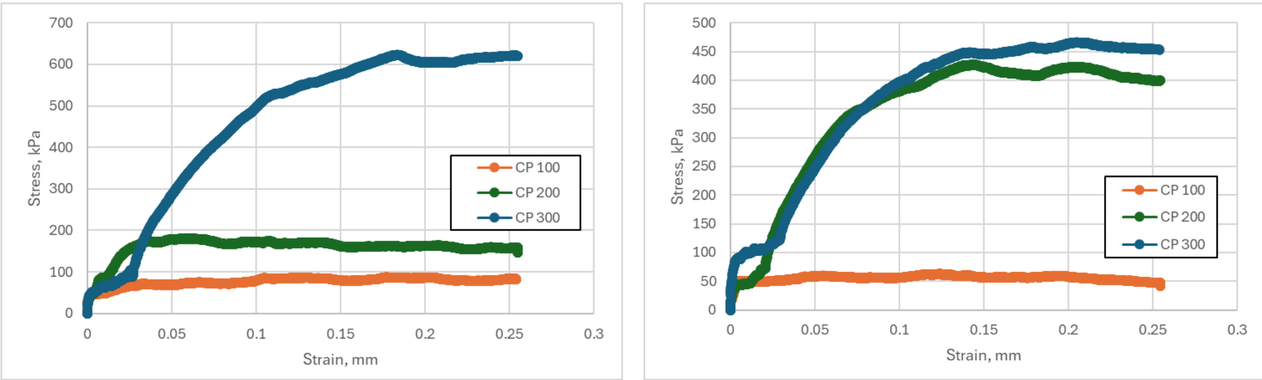
(a) (b)

Fig. 4. Stress-strain curve for untreated clayey sand sample in the UU test (a) trial 1 and (b) trial 2



(a) (b)

Fig. 5. Stress-strain curve for 2.5% LIG clayey sand sample in the UU test (a) trial 1 and (b) trial 2



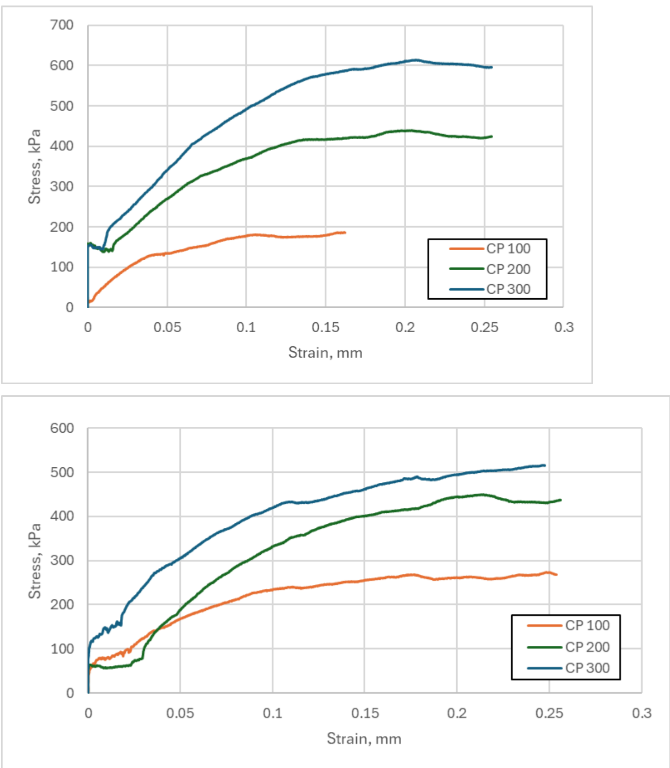
(a) (b)

Fig. 6. Stress-strain curve for (a) 5% and (b) 10% LIG clayey sand samples in the UU test

4.2 Consolidated Undrained (CU) Triaxial Test

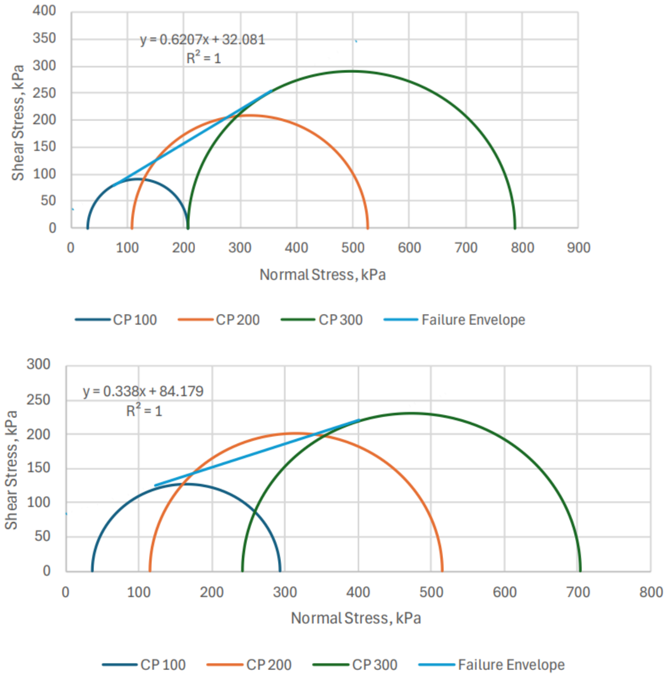
CU tests were limited to untreated soil and 2.5% LIG-treated soil, based on the favorable performance of this concentration in the UU tests. Strain-softening was observed throughout the shearing phase at varying confining pressures, indicating a ductile mode of failure with deviator stress at failure occurring at 15% strain. An increase in confining pressure generally corresponded to an increase in deviator stress along the axial strain. The stress-strain curves for 200 and 300 kPa shown in Fig. 7a revealed a clear yield point, indicating an initial elastic response prior to plastic deformation. Higher confining pressures also led to higher peak stresses, suggesting the untreated soil could withstand greater stress under higher confinement.

Similarly, the stress-strain curves for the soil treated with 2.5% lignin shown in Fig. 7b also observed strain-softening throughout the shearing phase at varying confining pressures, indicating a ductile mode of failure with deviator stress at failure at 15% strain. As with the untreated soil, increasing confining pressure resulted in an increase in deviator stress along the axial strain, demonstrating enhanced shear strength. The presence of a yielding point was also observed for the 200 kPa and 300 kPa tests on the treated soil. After reaching the deviator stress, the curves plateaued, indicating plastic deformation without a significant stress increase. The higher peak stress and greater strain endurance before reaching the plateau at higher confining pressures for the treated soil demonstrate the effectiveness of lignin treatment in improving the shear strength and ductility of the clayey sand. These results align with the DPWH standards (Section 206.2.1) [20] which require materials to be hard, durable, and maintain structural integrity under various stress conditions.



(a) (b)

Fig. 7. Stress-strain curve for (a) untreated clayey sand and (b) 2.5% LIG clayey sand in the CU test



(a) (b)

Fig. 8. Mohr's circles for (a) untreated clayey sand and (b) 2.5% LIG clayey sand in the CU test

Effective stress Mohr's circles graphically represent the stress states accounting for pore water pressures. For the untreated clayey sand (Fig. 8a), the effective cohesion was found to be 32.08 kPa and the effective angle of internal friction was 31.83°. The analysis suggests that the soil's shear strength is significantly influenced by the reduction in pore water pressure, which increases inter-particle friction and overall stability. For the soil treated with 2.5% lignin (Fig. 8b), the effective cohesion was found to be 84.18 kPa and the effective angle of internal friction was 18.68°. The increase in cohesion due to the presence of 2.5% lignin is evident. These results align with the DPWH standards [20] requiring soil to exhibit adequate shear strength for stability in construction applications.

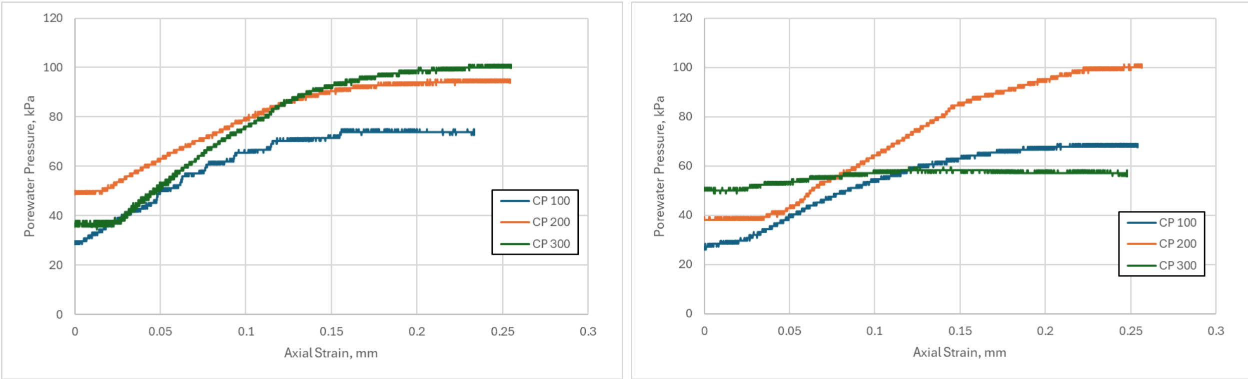
The excess porewater pressure coefficient (A_f) helps determine the type of clay used in the study. Table 2 presents the theoretical A_f values for each clay type while Table 3 presents the calculated A_f values for each CU test Based on these results, all soil samples were determined to be lightly overconsolidated clays, as A_f values below 1 indicate the sample being slightly overconsolidated prior to undrained compression. The pore water pressure graphs in Fig. 9 show that as all tests observed strain-softening in the stress-strain curves, the corresponding pore water pressure graphs observed compression during shearing, indicating ductile failure.

Table 2. Range of pore water pressure coefficients per clay type *[21]*

Type of Clay	A_f
Highly sensitive	0.75 to 1.0
Normally consolidated	0.50 to 1.0
Compacted sandy clay	0.25 to 0.75
Lightly overconsolidated clays	0 to 0.5
Compacted clay-gravel	-0.25 to 0.25
Heavily overconsolidated clays	-0.5 to 0

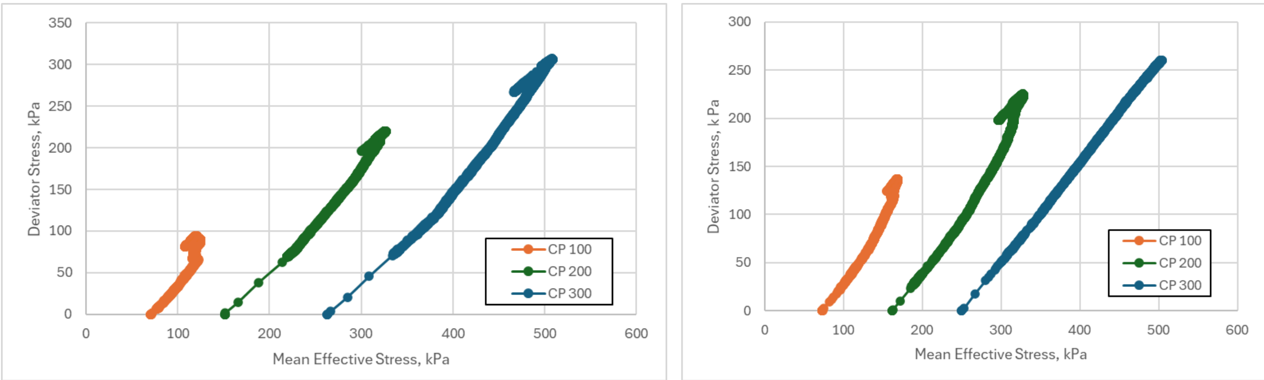
Table 3. Porewater pressure coefficient values per trial

Trial	A_f
0%, 100 kPa	0.40
0%, 200 kPa	0.22
0%, 300 kPa	0.16
2.5%, 100 kPa	0.25
2.5%, 200 kPa	0.21
2.5%, 300 kPa	0.13



(a) (b)

Fig. 9. Porewater pressure plots for (a) untreated clayey sand and (b) 2.5% LIG treated clayey sand



(a) (b)

Fig. 10. Stress paths for (a) untreated clayey sand and (b) 2.5% LIG treated clayey sand

Stress paths, plotted with deviator stress (q) on the vertical axis and mean effective stress (p') on the horizontal axis also provided insights into the stress-strain behavior and loading history of soils. For the untreated soil (Fig. 10a), the stress paths generally present an upward trend, showing increasing deviator stress with increasing mean effective stress. Steeper slopes at 200 kPa and 300 kPa suggest the clayey sand can endure higher stresses before failure. This stress path pattern shows a usual trend of strain hardening. Higher confining pressure allows the untreated clayey sand to withstand higher deviator stresses, indicating enhanced stability.

For the 2.5% lignin treated soil (Fig. 10b), the stress paths also show an increase in deviator stress with mean effective stress. The curve at 100 kPa shows a non-linear increase, indicating a reduction in stiffness as it approaches failure. The stress paths for 200 kPa and 300 kPa show similar trends but at higher stress levels, indicating higher strength. The treated soil's strength increases with higher confining pressure, which is typical for soils and enhances resistance to shear deformation. Comparing the treated and untreated stress paths, the 2.5% LIG treated soil showed higher deviator stress at 100 kPa compared to the untreated soil. However, the deviator stresses for 200 kPa were relatively similar, and at 300 kPa, the treated soil showed a decrease in deviator stress with mean effective stress compared to the untreated soil. The stress path analysis for the 2.5% treated soil depicts increasing strength and stiffness with higher confining pressure.

Table 4 summarizes the effective cohesion (c') and angle of internal friction (ϕ') obtained from the CU tests. When compared to typical shear strength parameters for clayey sands provided by the National Highway Institute (1997) the results fall within expected ranges. For untreated soil, the effective cohesion was 32.08 kPa and the friction angle was 31.83°, aligning closely with the typical saturated cohesion of 50 kPa and the standard friction angle range of 31±4° for SC-classified soils. In contrast, soil treated with 2.5% lignin showed a significantly higher cohesion of 84.18 kPa, indicating improved bonding. However, the friction angle decreased to 18.68°, which aligns with findings by Bagheri et al. [4], which explained that lignin may coat soil particles and reduce their surface roughness, thus lowering friction.

Table 4. Shear strength parameters calculated from CU test samples

Sample	c’	ϕ'
0% LIG	32.08 kPa	31.83°
2.5% LIG	84.18 kPa	18.68°

Table 5 presents the effective shear stresses at failure under varying confining pressures. Both untreated and lignin-treated soils exhibited increased shear stress at failure with higher confining pressure. The 2.5% lignin-treated soil generally displayed higher shear strength than the untreated sample at 100 kPa and 200 kPa. However, at 300 kPa, the treated soil showed slightly lower shear strength compared to the untreated soil.

Table 5. Effective shear stress at failure for untreated and treated samples at varying confining pressures

Sample	100 kPa	200 kPa	300 kPa
0% LIG	78.52 kPa	143.07 kPa	253.24 kPa
2.5% LIG	125.31 kPa	163.00 kPa	219.86 kPa

5. CONCLUSION

The study aimed to evaluate the effect of lignin biopolymer (LIG) on the shear strength of Zamboanga ultisol. Initial attempts were made to extract lignin from coconut husk, but due to a low yield, commercially purchased lignin was used for experiments. The purity and molecular structure of both the extracted and purchased lignin were confirmed using FT-IR analysis by comparison against a known standard. Unconsolidated undrained (UU) triaxial tests were conducted on untreated soil and soil treated with 2.5%, 5%, and 10% LIG at confining pressures of 100 kPa, 200 kPa, and 300 kPa. The undrained shear strength results from the UU tests exhibited significant variability, with percentage differences ranging from 30.04% to 147.69% compared to the untreated soil. This variability was primarily attributed by the researchers to the difficulties encountered in consistently replicating the arrangement and structure of soil particles during the moist tamping sample preparation method. Despite the variability, the 2.5% LIG concentration indicated apotential for improving undrained shear strength, particularly observed at the 300 kPa confining pressure, leading to its selection for further detailed analysis. Higher LIG concentrations (5% and 10%) did not demonstrate the same consistent level of improvement in the UU tests.

Further investigation involved consolidated undrained (CU) triaxial tests, performed on the untreated soil and the soil treated with the selected 2.5% LIG concentration under confining pressures of 100 kPa, 200 kPa, and 300 kPa. These CU tests provided clearer insights into the treated soil's shear strength parameters. The addition of 2.5% LIG resulted in a significant increase in both total and effective cohesion, more than doubling the cohesion measured in the untreated control sample. Conversely, the CU tests revealed a decrease in the total and effective angle of internal friction with the 2.5% LIG additive. This reduction in friction angle was linked to the lignin coating the soil particles and reducing their surface roughness. While the 2.5% LIG samples showed improved total and effective stresses at 100 kPa and 200 kPa confining pressures compared to the untreated soil, stresses decreased at 300 kPa confining pressure.

Pore water pressure measurements during CU tests indicated compression during shearing, consistent with ductile failure behavior, and A_f values suggested the soils were lightly overconsolidated. Overall, the analysis of these results indicated that despite the variability observed in the UU tests, the CU tests confirmed that the 2.5% LIG concentration favorably influenced the soil's shear strength parameters by significantly enhancing cohesion and altering friction characteristics.

These results corroborate prior studies that identified LIG's ability to enhance soil mechanical properties by filling voids and coating particles, thereby altering particle interaction mechanisms. The enhanced performance at 2.5% suggests an optimal concentration, whereas higher percentages may inadvertently reduce shear strength due to excessive lubrication.

Given its renewable origin and low environmental impact, LIG shows promise as a sustainable soil stabilization agent for clayey sands in humid tropical regions. However, further research is warranted to evaluate the long-term durability of lignin-stabilized soils, their performance under cyclic loading or varying moisture regimes, and the efficacy of alternative lignin sources or extraction techniques.

6. REFERENCES

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