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Statistical Validation of 2% Lignosulfonate as a Sustainable Stabilizer for Expansive Clay

A. Rivianto[1], A. I. Candra[2*], F. Nursandah[3], I. Mustofa[4]

[1,2*,3,4]*Civil Engineering Department, Faculty of Engineering, Kadiri University, Kediri, Indonesia*

Email: [1]arifrivianto74@gmail.com, [2*]iwan_candra@unik-kediri.ac.id, [3]fauzie_nursandah@unik-kediri.ac.id, [4]imammustofa@unik-kediri.ac.id.

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A B S T R A C T

Expansive clay soils undergo volumetric changes due to fluctuations in moisture content, which can cause structural damage to foundations, pavements, and embankments. Traditional stabilization methods, such as cement and lime, are effective but have a significant environmental impact, highlighting the need for more environmentally friendly alternatives. Lignosulfonate (LS), an organic stabilizer derived from industrial by-products, offers a more sustainable approach to improving soil strength and stability. This study evaluates the effect of 2% lignosulfonate on the unconfined compressive strength (UCS) of expansive clays. The research method involved mixing LS at 2% of the dry weight of the soil into the expansive clay (CL-ML) and conducting UCS tests on three untreated (control) samples and six treated samples. Statistical analysis was used to assess the significance of the differences between the two groups. Results show that the UCS increased from 236.29 kPa in the control group to 291.49 kPa in the treated group, reflecting a 23.37% improvement. Poisson's ratio decreased from 0.300 to 0.200, indicating reduced lateral deformation and enhanced soil stiffness, which improves the bearing capacity and stability of structures built on it. The UCS values were observed to be consistent supported by low standard deviation. The study highlights the critical role of adequate sample replication and control over operational variables such as moisture content, compaction, and LS dispersion to ensure reliable and reproducible stabilization outcomes. This study strengthens the empirical basis for the application of LS as a sustainable and environmentally friendly stabilizer for expansive clays.

1. Introduction

Expansive clay is a major geotechnical challenge, particularly in tropical regions such as Indonesia [1]. It is extensively distributed across coastal plains, covering approximately 20

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million hectares, constituting 10% of Indonesia's total land area. This soil is highly susceptible to moisture fluctuations due to seasonal variations, leading to significant volumetric changes. The resulting loss of soil stability and bearing capacity can cause severe damage to building foundations, roadways, and utility networks [2], [3], [4], [5], [6]. The economic losses attributed to expansive clay are estimated at $9 billion annually in the United States, €3.3 billion in France (2002), and $15 billion in China, as reported in studies documenting infrastructure damage caused by soil instability, leading to cracks and structural failures [7], [8], [9]. Although specific quantitative data remain undocumented in Indonesia, expansive clay has been responsible for various geotechnical issues, particularly in humid regions with high rainfall.

Cement and lime are the most commonly used stabilization materials for addressing expansive clay issues [10], [11], [12], [13]. Cement enhances soil strength through pozzolanic reactions, while lime reduces plasticity through ion exchange processes [14], [15]. Despite their effectiveness, cement and lime stabilization have certain limitations. Cement production generates carbon emissions ranging from 0.7 to 1.1 tons of CO_2 per ton, contributing to global warming [16], [17], [18]. Moreover, these materials have long-term environmental impacts, such as groundwater quality deterioration due to pH alterations [19]. Therefore, more environmentally friendly, efficient, and sustainable soil stabilization alternatives are required to mitigate these adverse environmental effects.

In addition to lime and cement, various industrial by-products such as fly ash, rice hull ash, and other pozzolanic materials have been widely used in soil stabilization due to their cementitious properties. However, these materials often exhibit variability in composition, limited biodegradability, and in some cases, challenges related to heavy metal content. In contrast, lignosulfonate (LS) offers several advantages, including its organic nature, high biodegradability, non-toxic profile, and consistent chemical composition. Accordingly, lignosulfonate (LS) is an organic stabilizer derived from industrial pulp and paper waste that offers a promising and abundant (more than 100 million tons/year) environmentally friendly solution for sustainable soil stabilization [20], [21], [22], [23], [24], [25], [26], [27]. LS exhibits unique properties that enhance the soil's Unconfined Compressive Strength (UCS) through chemical bonding with soil particles. LS enhances mechanical strength by adhering to soil particles through forming clay particle clusters, flocculating sharp particles, and integration within the soil matrix [20], [28], [29].

Previous studies have shown that adding 2% LS can increase the UCS of low-plasticity soils to 450 kPa after seven days of curing with three replications [30]. In high plasticity soils, the UCS increased to 215 kPa [26]. In medium plasticity soils, a combination of 2% LS and

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lime in an expansive soil improved the UCS to 240 kPa [31]. In highly plastic soils, the 2% LS mixture increased UCS to 292.5 kPa after seven days of curing [27]. Another study reported that seven days of LS treatment in highly plastic soils resulted in a UCS of 212.58 kPa [32]. These results highlight the potential of LS as a soil stabilizer. However, on closer inspection, most previous studies have used minimal replication, typically three times, which limits the reliability and statistical representativeness of the results. This gap highlights the need for more comprehensive studies with sufficient replication to ensure the consistency and validity of the observed strength enhancement.

The lack of systematic studies with adequate replication has hindered the reliability and generalizability of findings on the effectiveness of lignosulfonate (LS) as a soil stabilizer. Many previous investigations suffer from limited sample sizes and insufficient statistical rigor, resulting in inconsistent conclusions regarding their effect on soil strength. Technical inconsistencies in laboratory data can have significant implications in engineering practice, where unreliable strength parameters can lead to suboptimal design, increased construction costs, or structural failure. Therefore, this study aimed to evaluate the effect of 2% LS on the unconfined compressive strength (UCS) of expansive clays. Six replicates were used for the treated group and three for the control to ensure data consistency. The achieved consistency can strengthen the reliability of LS as a sustainable stabilizer for expansive soils. This study provides an empirical basis for adopting LS for practical applications and reducing dependence on conventional stabilizers such as cement and lime. Thus, adopting LS can increase bearing capacity, reduce settlement, and minimize the risk of volumetric instability under fluctuating moisture conditions.

2. Research Method

This study employs laboratory experiments to evaluate the effect of lignosulfonate (LS) on the Unconfined Compressive Strength (UCS) of expansive clay. The study was conducted at the Civil Engineering Laboratory of Universitas Kadiri, which is equipped with soil testing facilities that comply with ASTM standards. ASTM D2166 conducted testing to ensure the validity of the results.

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2.1 Materials

Source: Google Earth (2024).

Figure 1. Sampling Location Map

Expansive clay samples located behind Kadiri University, as shown in Figure 1, were collected from a depth of 50–100 cm, with montmorillonite identified as the primary mineral. The total sample set consisted of six replications (L1-L6) for the LS-treated group and three replications (K1-K3) for the control group. The decision to utilize a greater number of treatment samples was a deliberate research choice with the objective of enhancing data reliability, in contrast to the approaches adopted in previous studies.

Table 1. Physical Properties of Soil

Test	Test Standard	Result
Specific gravity	ASTM D-854	2.72
Cu	ASTM C136	5.91
Cc	ASTM C136	1.43
LL	ASTM D-4318	24.04
PL	ASTM D-4318	19.80
PI	ASTM D-4318	4.24
USCS		CL-ML

Source: Author's Research Results (2025).

Table 2. Chemical Properties of Lignosulfonates

Parameters	Value	Chemical Mixture	Percentage (%)
Physical state	Powder	C	60.98
Appearance	Chocolate	SO_3	19.77
Solubility	Soluble in Water	CaO	17.37
Gs	1.2 Approx	Al_2O_3	0.72
pH value	4–6	MgO	0.47
		K_2O	0.29
		Na_2O	0.12

Source: Previous Research (2020) [25].

2.2 Research Procedure

Soil samples were collected from the research site and stored in sealed containers to preserve their natural moisture content. Before testing, the soil was oven-dried at approximately 105°C for 24 hours and sieved through a 4.75 mm mesh to ensure grain size uniformity. The

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optimum moisture content of 17.98% and maximum dry density (MDD) of 1.65 kN/m³ were determined using the Standard Proctor test. Soil compaction was performed at 95% of MDD to represent typical civil engineering conditions used in infrastructure construction. The soil samples were divided into two groups: an untreated control group and a treatment group stabilized with lignosulfonate (LS), a commercially available additive commonly purchased from online suppliers. In the treatment group, the soil was mixed with 2% LS by dry weight and manually stirred using a laboratory spatula to ensure even distribution. Each sample was molded into a UCS cylindrical specimen (35 mm in diameter, 70 mm in height) and statically compacted in three uniform layers to prevent material segregation and ensure optimal density distribution. After compaction, the specimens were left for 7 days to cure at 27°C, allowing the LS to interact with the soil particles and allow bonding and strength to develop. According to ASTM D4609 (1994) and previous studies, soils treated with other materials should be cured for 28 days [33], [34], [35], [36]. However, other studies have shown that 7 days can show effective initial stabilization [37].

2.3 Data Processing and Analysis

The results of the UCS test are in the form of maximum stress values in KPa units and Poisson ratio. The measurement of Poisson's ratio describes the relationship between lateral deformation and axial deformation when the material is loaded. Poisson's ratio value for soil ranges from 0 to 0.5, depending on the soil type and its consolidation conditions. Poisson's ratio is calculated using the following **Equation 1**.

$$\nu = \frac{\epsilon_{lateral}}{\epsilon_{axial}} = \frac{\Delta D/D_0}{\Delta H/H_0} = \frac{(D_f - D_0)/D_0}{(H_0 - H_f)/H_0} \quad (1)$$

Where D_0 is the initial diameter, D_f is the final diameter, H_0 is the initial height, H_f is the final height. The change in diameter (ΔD) is defined as $D_f - D_0$, and the change in height (ΔH) is defined as $H_0 - H_f$. The lateral strain ($\epsilon_{lateral}$) represents the relative change in diameter, while the axial strain (ϵ_{axial}) represents the relative change in height during loading.

Data analysis was conducted to evaluate the distribution, significance, and reliability of the Unconfined Compressive Strength (UCS) results. Descriptive statistics were employed to determine the mean, standard deviation, and UCS value range, providing insights into data distribution and variability. A one-way ANOVA test was applied to assess significant differences between the control and treated groups, evaluating the effect of lignosulfonate on the strength of expansive clay. Result validation was performed using six replications for the LS-treated samples and three for the control samples, in accordance with ASTM D2166, to ensure consistency and reliability.

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3. Results and Discussions

3.1 Unconfined Compressive Strength (UCS)

Table 3 shows the unconfined compressive strength (UCS) results for the control group (no lignosulfonate) and the group treated with 2% lignosulfonate (LS) with the same curing time of 7 days. The average UCS for the control group was 236.28 kPa, while the group treated with 2% LS had a much higher average UCS of 291.49 kPa, indicating a significant increase in soil strength of approximately 23.37%.

Table 3. UCS Test Results

Code	Maximum Stress (KPa)	Average
K1	233.11	
K2	239.24	236.28
K3	236.51	
L1	296.66	
L2	280.26	
L3	295.71	291,49
L4	300.76	
L5	291.19	
L6	284.36	

Source: Author's Research Results (2025).

In comparison with the control samples (not treated with LS), the samples treated with LS (2% LS) demonstrate a distinctly broader UCS range (280.26–300.76 kPa vs. 233.11–239.24 kPa). This increased range in the treated group indicates a greater degree of variability among the replicates. This could be due to several factors, such as inconsistencies in LS dispersion, compaction effort, or moisture content during sample preparation.

The substantial rise in UCS values underscores the efficacy of 2% LS in augmenting inter-particle bonding and cohesion, consequently significantly enhancing soil-bearing capacity. Previous studies have also endorsed the utilization of 2% LS in diverse soil types, though they frequently relied on a reduced number of replicates (typically three), thereby impeding the capacity to discern variability. In contrast, the present study incorporated six replicates for the LS-treated group, thus enabling a more comprehensive statistical evaluation. Despite the presence of some variation, the consistent improvement in UCS across these samples reinforces the conclusion that 2% LS is a reliable and repeatable soil stabilizer for clay soils.

3.2 Stress-Strain

Figure 2 presents the stress-strain relationship for both the control and LS-treated soil samples. The data illustrate the maximum stress achieved and the strain behavior of each group.

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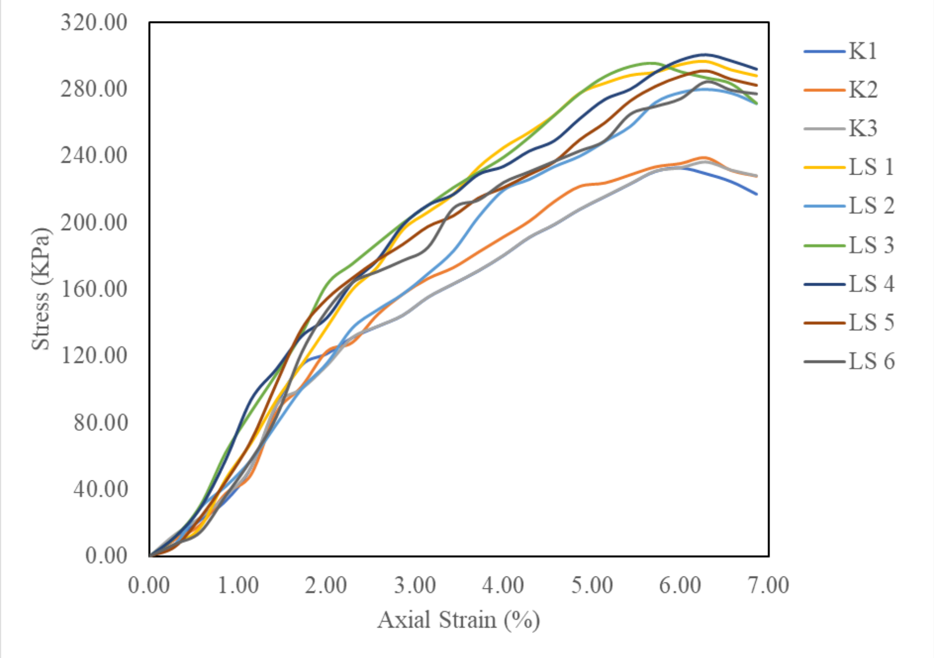

Source: Author's Research Results (2025).

Figure 2. Stress-Strain Curve

Figure 2 depicts the stress-strain behavior of soil samples with and without LS treatment. The control soil (K1, K2, K3) exhibits greater plastic deformation, characterized by a more gradual increase in stress and a higher axial strain at failure. In contrast, LS-treated soil (LS1–LS6) demonstrates a steeper initial slope in the stress-strain curve, indicating increased stiffness and elastic modulus. The treated sample also achieved a higher peak stress at LS4 reaching 300.76 KPa, indicating an increased soil load-bearing capacity. Furthermore, the LS-treated samples exhibit reduced axial deformation before failure, implying improved resistance to compressive loading. These findings highlight the effectiveness of LS treatment in enhancing soil stability for civil engineering applications such as foundations, embankments, and subgrade improvements.

3.3 Poisson's Ratio

Table 4 presents the values of Poisson's ratio**.** The reduction in Poisson's ratio from 0.300 to 0.200 demonstrates that LS treatment enhances axial strength while simultaneously reducing lateral deformation. This improvement contributes to increased soil stability, making LS a promising stabilizer for shallow foundations and geotechnical structures such as retaining walls and embankments.

Table 4. Poisson's Ratio Results

Group	Number of Sampel	Mean Poisson Ratio	Standard Deviation
Control	3	0,300	0,018
LS Treatment	6	0,200	0,005

Source: Author's Research Results (2025).

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3.4 Statistical Analysis

Descriptive statistical analysis was conducted to evaluate the UCS data's mean, standard deviation, value range, and 95% confidence interval. The results are summarized in **Table 5**, while the results of the one-way ANOVA test are shown in **Table 6**.

Table 5. Descriptive Statistics of UCS Values

Group	Number of Samples (N)	Mean (KPa)	Standard Deviation (KPa)	95% Confidence Interval	Minimum Value (KPa)	Maximum Value (KPa)
Control	3	236.29	3.07	228.66 – 243.92	233.11	239.24
LS Treatment	6	291.49	7.84	283.26 – 299.72	280.26	300.76

Source: Author's Research Results (2025).

Table 6. ANOVA Results for UCS Values

Sources of Variation	Sum of Squares	df	Mean Square	F	Sig.
Intergroup	6.094.816	1	6.094.816	130.721	0.000
Within Group	326.373	7	46.625		
Total	6.421.189	8			

Source: Author's Research Results (2025).

The experimental findings indicate a statistically significant unconfined compressive strength (UCS) enhancement due to lignosulfonate (LS) treatment. The mean UCS of the LS-treated specimens (291.49 kPa) significantly exceeds that of the untreated control group (236.29 kPa), with non-overlapping 95% confidence intervals (228.66–243.92 kPa for control; 283.26–299.72 kPa for LS-treated). This clear separation serves to affirm a true difference in population means. While the standard deviations remain relatively low for both groups (3.07 kPa for the control group and 7.84 kPa for the LS-treated group), the broader UCS range observed in the treated samples suggests the presence of influencing variables that affect intra-group consistency. The potential factors contributing to this variation include variability in moisture content, compaction energy, LS dispersion uniformity, and curing conditions. Notwithstanding rigorous control measures, minor discrepancies during sample preparation may introduce heterogeneity, particularly in chemically treated soils. These findings emphasize the necessity of standardized procedures in future applications of LS as a stabilizing agent. Ensuring consistency in the mentioned parameters has been shown to mitigate performance variability and optimize the mechanical enhancement of cohesive soils.

The findings of this study are corroborated by the statistical analysis, which includes a one-way ANOVA that yielded a highly significant F-value (130.721) and p-value (<0.001). This analysis confirms that the observed improvement in UCS cannot be attributed to random

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variation. Furthermore, using six replicates for the treated group enhances the robustness of the dataset, offering a more reliable assessment of LS's stabilizing efficacy compared to previous studies with limited replication. The incorporation of 2% LS has been demonstrated to improve the mechanical behavior of clay soils. However, it is imperative to emphasize the significance of careful attention to operational variables in ensuring the reproducibility and scalability of the stabilization process in field applications.

3.5 Correlation with Previous Studies

Table 7 presents the correlation results between this study and previous research, while **Table 8** provides the ANOVA analysis comparing UCS values.

Table 7. Correlation with Previous Studies

Author	Soil Type	UCS (kPa)	Number of Samples
[30]	Low-plasticity	450	3
[26]	High-plasticity	215	Unknown
[31]	Medium-plasticity	240	Unknown
[27]	High-plasticity	292.5	Unknown
[32]	High-plasticity	212.58	3
This research	Low-plasticity	291,49	6

Source: Author's Research Results and Previous Research (2025).

Table 8. ANOVA Results for Correlation with Previous Studies

Statistics	Value
F-statistic	0.051
p-value	0.832

Source: Author's Research Results (2025).

This study demonstrates that applying 2% lignosulfonate (LS) effectively enhances expansive clay soil's Unconfined Compressive Strength (UCS) by 23.37%, increasing from 236.29 kPa to 291.49 kPa. The ANOVA analysis confirms that the UCS differences between this study and previous research are statistically insignificant (p-value = 0.832), reinforcing the validity and consistency of the findings. Compared to previous studies that reported a UCS of 450 kPa for low-plasticity soils with only three replications, this research emphasizes higher accuracy by employing six replications per treatment. Furthermore, the findings highlight the efficiency of LS as a standalone stabilizer, in contrast to previous studies that combined LS with lime or polypropylene fibers [28], [31]. These results significantly contribute to geotechnical engineering, particularly in developing reliable and efficient soil stabilization methods using LS as a single additive for problematic soils.

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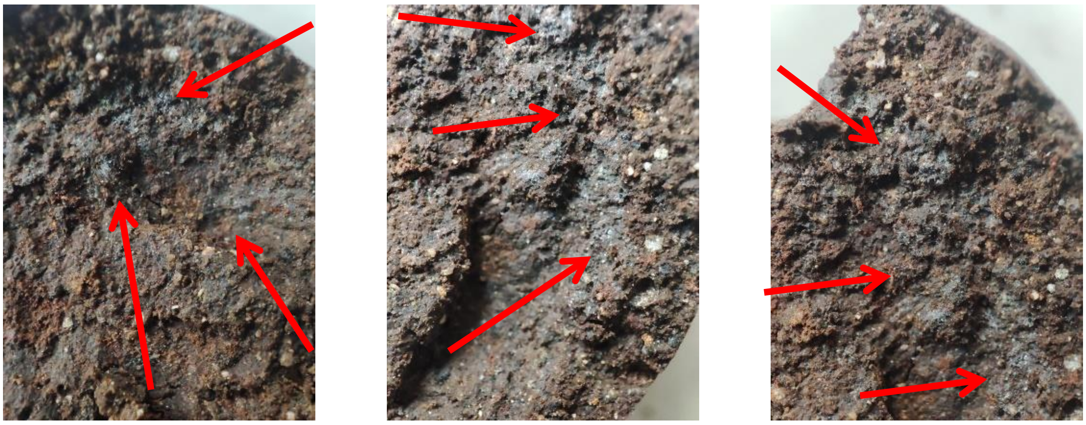
3.6 Effect of 2% LS Addition on UCS



Source: Author's Research Results (2025).

Figure 3. Microstructural of LS in Soil

Figure 3 illustrates the microstructural changes in soil samples treated with 2% LS, highlighting increased particle aggregation and decreased pore volume. The red arrows in the image identify areas where cohesion is enhanced and microcracks are reduced due to LS addition, leading to improved soil structure and stability. This improvement is attributed to the adsorption of LS onto soil particle surfaces, which promotes flocculation and the formation of ionic and hydrogen bonds between clay particles [38]. The LS adsorption process strengthens soil consolidation, increases cohesion, and reduces pore volume [39], [40], [41]. The polymeric bonding formed through LS-soil interaction reduces water retention and enhances soil density, thereby directly improving load-bearing capacity and soil stability against moisture fluctuations [37].

4. Conclusion

This study concludes that adding 2% lignosulfonate (LS) to expansive clay soils significantly increases unconfined compressive strength (UCS), with consistent results across multiple replicates. The observed consistency in UCS values, supported by a low standard deviation and a sufficient number of replications, addresses the limitations of previous studies that lacked data reliability due to minimal sample sizes. The study highlights the critical role of adequate sample replication and control over operational variables such as moisture content, compaction, and LS dispersion to ensure reliable and reproducible stabilization outcomes. This study strengthens the empirical basis for using LS as a sustainable and environmentally friendly stabilizer for expansive clays, with promising implications for practical geotechnical engineering applications.

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