Sustainable Stabilization of Tropical Residual Lateritic Soils Using Xanthan Gum

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Abstract

Tropical residual soils generally exhibit low strength and stability due to intensive weathering and high rainfall, posing significant challenges for construction and soil stabilization. Conventional stabilization methods such as cement can improve soil strength but have substantial environmental impacts, including high carbon emissions and considerable energy consumption. This study aims to evaluate the effect of xanthan gum (XG) as an environmentally friendly stabilizing agent on the mechanical and permeability properties of tropical residual soils under both dry and soaked conditions. The experimental program included physical characterization, Unconfined Compressive Strength (UCS), Triaxial Unconsolidated Undrained (UU), and permeability testing using the Falling Head method. The soil was classified as high-plasticity silt (MH) with a maximum dry density of 1.26 g/cm³ and an optimum moisture content of 37%. The addition of XG increased UCS from 7.43 kg/cm² (0% XG) to a maximum of 19.08 kg/cm² at 3% XG, which represents the optimum content for enhancing UCS, before decreasing at higher contents. Under dry conditions, cohesion increased from 3.15 kg/cm² to 8.00 kg/cm² (3% XG), while the internal friction angle decreased from 6.50° to 2.05°. In soaked conditions, XG still improved shear strength compared to untreated soil, although deviator stress decreased by approximately 86.47% to 88.88% compared to dry conditions. Permeability was reduced by up to 92%, from 2.6350×10^{-6} cm/s to 1.937×10^{-7} cm/s at 3% XG. Additionally, the Plasticity Index increased from 22.4 (0% XG) to 56.4 (6% XG), indicating a potential swelling–shrinkage problem in XG-stabilized soils.

Keywords: xanthan gum, UCS, Triaxial UU, Permeability, Swelling.

1. INTRODUCTION

Tropical residual soils are widespread in Indonesia and many other equatorial regions, forming in situ from the intense weathering and decomposition of parent rock materials (1,2). Their formation is strongly influenced by high rainfall, leading to the removal of bases and silica and the accumulation of iron and aluminum oxides. As a result, these soils often exhibit low to medium cohesion, high porosity, and reduced mechanical strength, which present substantial geotechnical challenges in infrastructure development and slope stabilization (3,4). Such properties often cause a decline in bearing capacity and long-term instability, especially in tropical regions subject to continuous rainfall and leaching processes.

The stabilization of tropical residual soils is vital for ensuring safe and sustainable infrastructure. Traditionally, cement and lime have been widely used as stabilizing agents, but these materials are associated with significant environmental drawbacks, notably greenhouse gas emissions and high energy consumption during their manufacture (5). This has driven the search for alternative, eco-friendly soil stabilizers. One promising approach is the use of biopolymers such as xanthan gum, a naturally derived polysaccharide capable of forming strong bonds with soil particles through physicochemical interactions(6,7)

Recent studies have demonstrated that xanthan gum can improve the shear strength and durability of soils, with optimal effects observed at low concentrations (1-2%) (8,9). However, a key issue that remains underexplored is the performance of xanthan gum-stabilized soils when subjected to direct water exposure or soaking, which is highly relevant to tropical environments where leaching and saturation are common. Most previous research has not sufficiently addressed the influence of such conditions, creating a knowledge gap in the practical application of xanthan gum as a sustainable soil stabilizer.

In response to these challenges, the present study aims to evaluate the mechanical and hydraulic improvement of tropical residual soil using xanthan gum, specifically examining its performance under both dry and soaked conditions. The findings are expected to provide important insights into the suitability and limitations of biopolymer-based soil stabilization for use in tropical regions, contributing to both the theoretical development and practical implementation of sustainable ground improvement technologies.

1.1. Theoretical Foundations of Tropical Residual Soils and Soil

The classification and behavior of tropical residual soils are anchored in fundamental soil science and geotechnical engineering theories. Residual soils are those that remain at the site of their parent rock, formed through a combination of physical, chemical, and biological weathering processes (1,2,10). The process of laterization in tropical regions leads to unique characteristics: enrichment in sesquioxide (Al_2O_3, Fe_2O_3), loss of bases and silica, and increased vulnerability to leaching and cementation loss, all of which undermine soil strength and structure (4,11).

In engineering practice, soil stabilization refers to methods for modifying soil properties to meet performance criteria such as shear strength, stiffness, and permeability. Approaches range from traditional (cement, lime) to innovative biopolymer-based solutions. Biopolymers, such as xanthan gum, work by forming networks with soil particles through hydrogen bonding and electrostatic interactions, reinforcing soil aggregates and enhancing stability (7,9).

This article addresses these gaps by empirically investigating the mechanical and permeability characteristics of xanthan gum-stabilized tropical residual soils under both dry and soaked conditions. By doing so, it complements and extends existing research, providing a robust scientific foundation for the broader adoption of biopolymer-based soil stabilization in tropical climates, and supporting the ongoing development of sustainable geotechnical engineering practices.

1.2. Previous Studies on Xanthan Gum and Soil Stabilization

Several key studies have contributed to the current understanding of xanthan gum as a soil stabilizer. A Study (8) experimentally compared cement and xanthan gum, showing that 1% xanthan gum outperformed 10% Portland cement in improving unconfined compressive strength of lateritic soil. In addition, study from (12,13) found xanthan gum yields optimal results with flexible application and significant strength gains after appropriate curing. The effectiveness of biopolymers in reducing permeability and improving wet-dry durability has been established (14). Polymer–soil interaction has been shown to increase the shear strength of tropical clays by up to 40% (9). Xanthan gum's ability to enhance liquid limit, cohesion, and internal stability by forming robust networks among soil particles has also been emphasized (7,15)

2. METHOD

2.1. Materials

Soil sampling of a typical tropical residual lateritic soil was carried out in West Java, Indonesia. Representative samples were excavated from depths ranging between 1 and 3 meters below the ground surface to capture the characteristics of the well-weathered residual soil horizon. Upon collection, coarse fragments such as pebbles and plant roots were carefully removed by hand. The soil was then air-dried under direct sunlight until it reached a stable moisture content suitable for further laboratory analysis. Figure 1 illustrates the particle size distribution curve obtained from the soil, while analysis Table 1 presents a summary of the key engineering properties of the natural soil evaluated in this study.

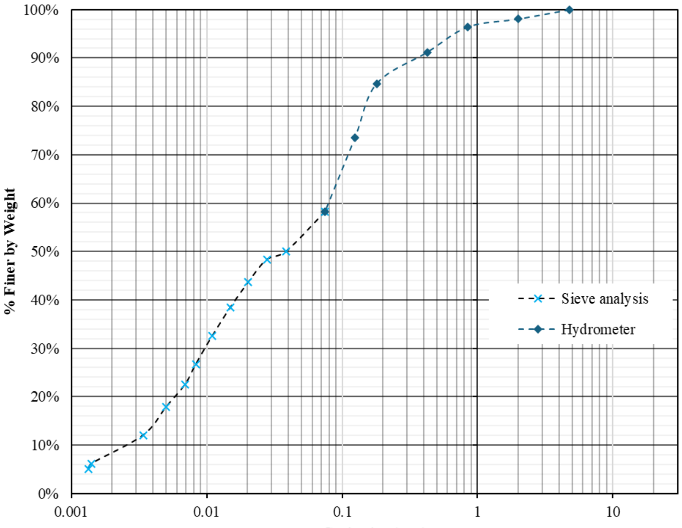
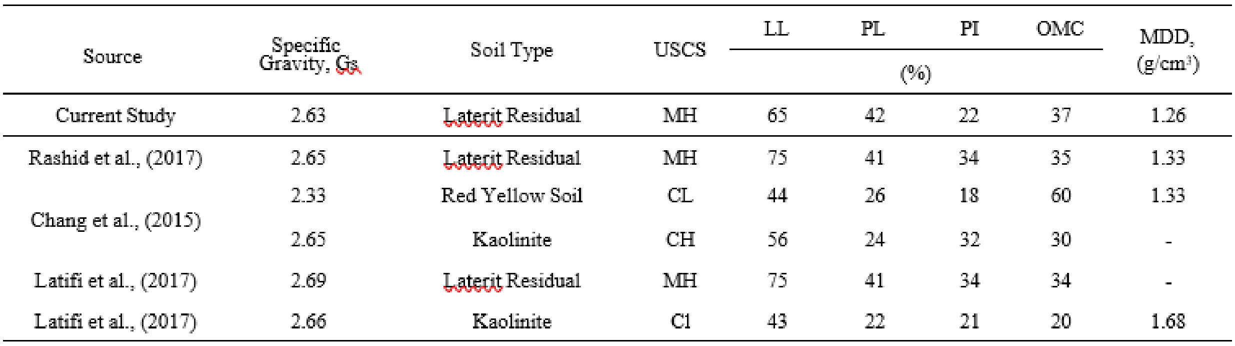


Fig. 1. Particle size distribution of the tested laterite soil

Table 1: Characteristics of the natural laterite clay



Source	Specific Gravity, Gs	Soil Type	USCS	LL	PL	PI	OMC	MDD, (g/cm³)
				(%)				
Current Study	2.63	Laterit Residual	MH	65	42	22	37	1.26
Rashid et al., (2017)	2.65	Laterit Residual	MH	75	41	34	35	1.33
Chang et al., (2015)	2.33	Red Yellow Soil	CL	44	26	18	60	1.33
	2.65	Kaolinite	CH	56	24	32	30	-
Latifi et al., (2017)	2.69	Laterit Residual	MH	75	41	34	34	-
Latifi et al., (2017)	2.66	Kaolinite	Cl	43	22	21	20	1.68

The physical properties in Table 1 indicate typical characteristics of tropical residual lateritic soils, including high plasticity, low natural moisture content relative to their liquid limit, and moderate to high specific gravity. These features reflect the dominance of fine particles and sesquioxides in the soil matrix, which contribute to strong interparticle bonding in dry conditions but increased susceptibility to strength loss upon saturation.

Xanthan gum is a natural polysaccharide produced by the fermentation of glucose or sucrose using the bacterium Xanthomonas campestris. Widely used as a food additive and rheology modifier, xanthan gum is known for its exceptional ability to increase viscosity even at low concentrations and for its remarkable stability over a broad range of temperatures and pH values (8,14,16,17). Beyond its applications in the food industry, xanthan gum has attracted considerable attention in geotechnical engineering due to its environmentally friendly characteristics and capacity to enhance the mechanical behavior of soils.

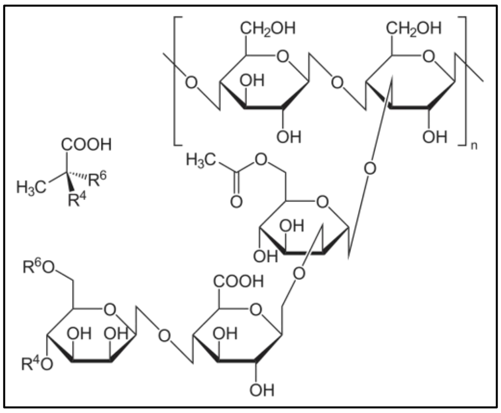


Fig. 2. Chemical structure of xanthan gum (Nugent et al., 2010)

The molecular structure of xanthan gum features negatively charged carboxyl (-COOH) and hydroxyl (-OH) groups, which enable it to interact strongly with soil mineral surfaces, particularly sesquioxide such as iron and aluminum oxides commonly found in tropical residual soils. Through these interactions, xanthan gum forms a polymer network that binds soil particles together, resulting in increased cohesion and a reduction in soil porosity (8,9). Experimental studies have shown that even small additions of xanthan gum, typically in the range of 1–2% by dry weight of soil can lead to significant improvements in unconfined compressive strength and shear resistance.

Furthermore, xanthan gum has been demonstrated to decrease soil permeability and improve durability against wetting-drying cycles, making it particularly suitable for stabilizing soils in tropical environments prone to intense rainfall and leaching (7,14). Its ability to retain water and maintain structure under varying moisture conditions differentiates xanthan gum from traditional stabilizers, while also minimizing environmental impact due to its biodegradable and non-toxic nature.

2.2. Sample Preparation

The soil samples were air-dried under direct sunlight to reduce moisture content while preventing potential alterations in the physico-chemical properties of the residual lateritic soil that may occur under oven-drying conditions(13,14). Coarse fragments and visible organic matter were carefully removed by hand to maintain sample integrity. The dried soil was then passed through a 2 mm sieve to obtain a uniform fine fraction suitable for laboratory mixing and compaction procedures.

Compaction characteristics were determined in accordance with the Standard Proctor Test (ASTM D698). This procedure established the optimum moisture content (OMC) and maximum dry density (MDD), which were subsequently used as reference parameters to ensure consistent and repeatable compaction of all prepared specimens. Xanthan gum was incorporated at varying concentrations: for unconfined compressive strength (UCS) testing, xanthan gum content ranged from 0% to 6% by dry weight of soil; for triaxial testing, the biopolymer was added up to 3%. Each batch was thoroughly mixed with deionized water to reach the previously determined OMC.

The moist, homogeneous mixture was compacted into cylindrical molds measuring 36 mm in diameter and 72 mm in height, in three equal layers, each layer being compacted to minimize air voids and achieve uniform density. This procedure ensured that specimens met the required consistency and geometry for both UCS and triaxial tests.

Curing was conducted under controlled laboratory conditions, ensuring that the specimens were protected from direct air flow and sunlight to minimize surface drying. For UCS specimens, a curing period of 21 days was maintained to promote the proper development of the xanthan gum soil matrix. Triaxial test specimens were cured for 14 days under the same protected conditions. Following the curing phase, selected triaxial specimens were fully submerged in water to simulate saturated field conditions prior to mechanical testing.

2.3. Testing Program

The experimental program was designed to systematically evaluate the mechanical and hydraulic performance of tropical residual soil stabilized with xanthan gum. Mechanical testing comprised Unconfined Compressive Strength (UCS) and Triaxial Unconsolidated Undrained, each performed on cylindrical specimens prepared with varying concentrations of xanthan gum.

UCS testing was carried out in accordance with ASTM D2166 on samples containing xanthan gum ranging from 0% to 6% by dry weight. During UCS testing, an axial load was applied to the specimens at a constant strain rate of 1% per minute until failure. All UCS specimens were subjected to a 21-day curing period in sealed containers to ensure optimal interaction between soil and biopolymer prior to testing. The UCS test aimed to determine the improvement in peak compressive strength attributable to xanthan gum addition.

Triaxial UU tests followed ASTM D2850 procedures and were conducted on specimens containing up to 3% xanthan gum, to investigate the influence of biopolymer stabilization on undrained shear strength parameters under both unsoaked (dry) and soaked (saturated) conditions. Triaxial specimens were cured for 14 days, with selected samples fully saturated by immersion prior to testing to simulate field exposure to prolonged wetting. During triaxial testing, axial load was applied at a constant strain rate of 2% per minute until failure or until 15% axial strain was reached. Shear strength parameters, including undrained cohesion and internal friction angle, were determined to evaluate the effects of xanthan gum under both dry and soaked scenarios.

In addition to mechanical assessment, falling head permeability tests were performed in accordance with ASTM D5084 to evaluate the impact of xanthan gum on soil hydraulic conductivity. This comprehensive testing program provided a robust assessment of the improvements in strength and permeability resulting from xanthan gum stabilization of tropical residual soils.

3. RESULTS AND DISCUSSION

3.1. Unconfined Compressive Strenght Test Result

The results show that the unconfined compressive strength (UCS) of the soil increased substantially with the addition of xanthan gum, reaching its peak at a content of 3%. The most notable strength improvements occurred at the lower xanthan gum dosages, particularly at 1% and 1.5%, where the UCS rose sharply from 7.43 kg/cm² (untreated) to 12.47 kg/cm² and 15.65 kg/cm², respectively. This early and pronounced enhancement highlights the effectiveness of xanthan gum even at low concentrations. The UCS continued to increase with higher xanthan gum content, achieving a maximum value of 19.08 kg/cm² at 3%. However, further addition beyond 3% resulted in a reduction in UCS, indicating the presence of an optimum dosage for xanthan gum stabilization. These findings underscore the importance of selecting an appropriate xanthan gum content to achieve maximum improvement in soil strength.

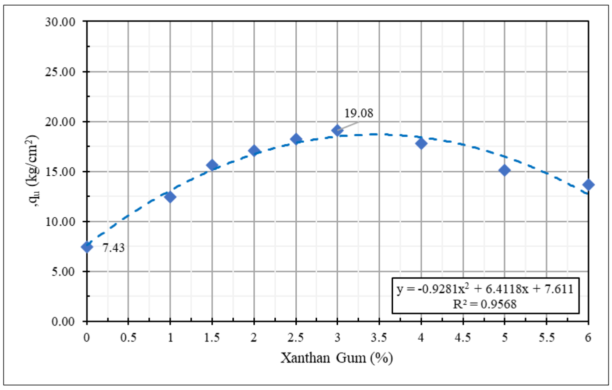


Fig. 3. UCS test results for treated laterite soil with different stabilizer contents

Test method drives much of the difference among studies. Higher compaction energy, such as Modified Proctor or gyratory, produces higher density and higher UCS. Sealed curing keeps moisture and delays polymer film hardening.

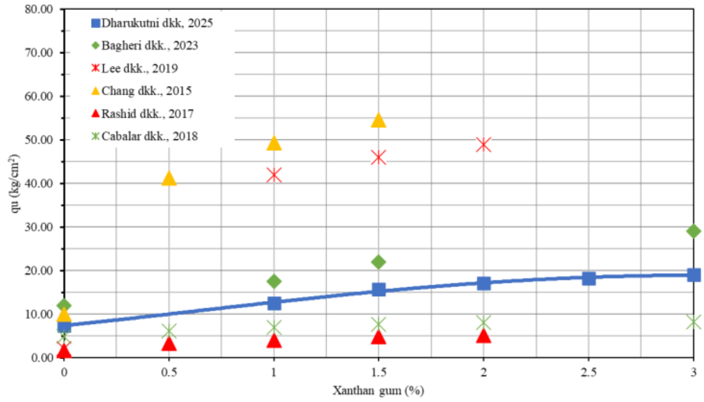


Fig. 4. UCS test results from various method

Fig. 3 compares the UCS results of the current study with previous works using xanthan gum as a soil stabilizer.

Overall, UCS increases with higher xanthan gum content, but variations among studies are evident due to differences in soil type, compaction method, and curing condition. In the current study, residual lateritic soil was compacted using the Standard Proctor method and cured under open-air laboratory conditions for 21 days, yielding a maximum UCS of 19.08 kg/cm² at 3% xanthan gum. Compared with (14), who obtained higher UCS using similar soil and compaction but plastic-wrapped curing, the lower values here are likely due to moisture loss during open-air curing.

Study form (16) achieved 29 kg/cm² using dry-mixing, layered compaction to >95% MDD, and partial plastic-wrapped curing. In addition, clay soil and Modified Proctor compaction with plastic-wrapped curing, produced lower UCS than the current study (7), suggesting that soil type strongly influences xanthan gum effectiveness (8). The highest UCS values (>49 and 54 kg/cm²) were obtained using high-plasticity soils and very high compaction energy, with the gyratory method (600 kPa × 50 cycles) producing dense, stable structures (6,18)

These comparisons confirm that xanthan gum performance depends on soil type, compaction energy, and curing method, aligning with findings that prolonged moisture retention followed by gradual drying optimizes biopolymer bonding (6,19).

3.2. Triaxial UU (Dry Condition)

Under dry conditions, the Triaxial UU test results demonstrated a significant increase in undrained shear strength with xanthan gum addition. The maximum undrained cohesion (Cu) reached 8.00 kg/cm² at 3% xanthan gum, compared to just 1.77 kg/cm² for untreated soil. However, the internal friction angle (ϕ) decreased from 6.5° to 2.05° as xanthan gum content increased.

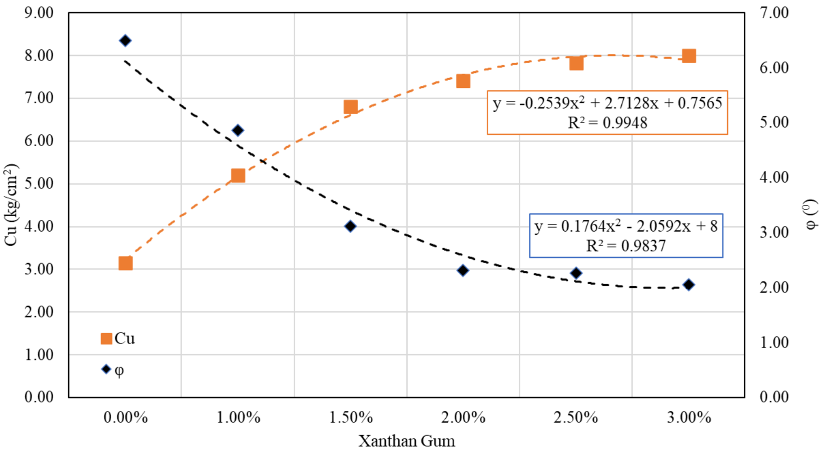


Fig. 5. Effect of xanthan gum content shear strength parameter under dry conditions from UU Triaxial tests

The increase in cohesion (Cu) observed in the current study is consistent with previous research, which has demonstrated that xanthan gum addition can significantly enhance soil shear strength through the formation of stronger interparticle bonds. The maximum cohesion achieved in this study was 8.00 kg/cm² at 3% xanthan gum, which is substantially higher than values reported in earlier studies, generally below 2.00 kg/cm² (9,14,17). This difference is attributed to variations in soil type, compaction method, and curing conditions. In this study, open-air curing for 21 days allowed gradual moisture loss, promoting progressive polymer bonding and resulting in improved shear resistance.

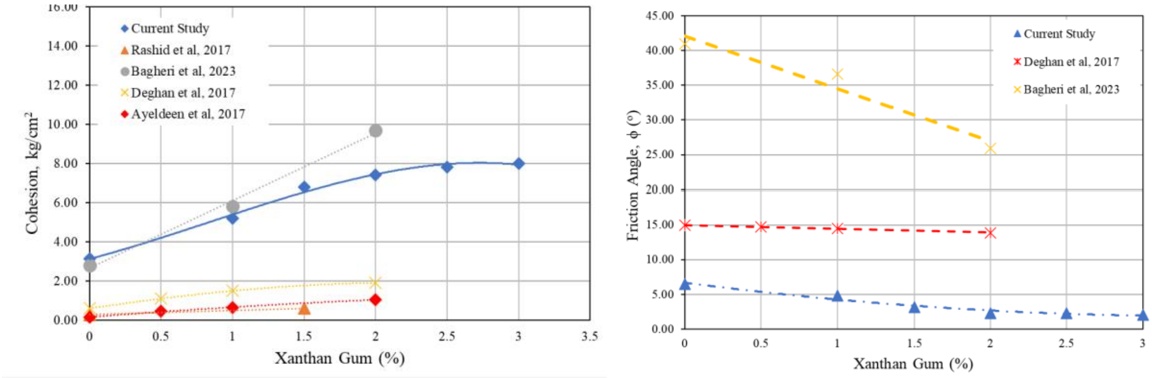


Fig. 6. (left) Cohesion (Cu) and (right) internal friction angle (ϕ) variation with xanthan gum content in the current study and previous research

In terms of internal friction angle (ϕ), a notable reduction from 6.50° to 2.05° was observed as xanthan gum content increased. This decrease is more pronounced than in other studies(16,17), where friction angle values remained relatively high. The marked reduction in ϕ indicates that the shear strength improvement in xanthan gum-stabilized soils is predominantly cohesion driven rather than reliant on particle interlocking. Similar trends have been reported in earlier works, which concluded that biopolymer application shifts the primary shear resistance mechanism from frictional contact between particles to polymer-induced bonding (7,13).

These findings confirm that the primary stabilization effect of xanthan gum lies in enhancing cohesion through interparticle bonding, albeit with a concurrent reduction in friction angle. This outcome has important implications for engineering applications, particularly in scenarios where undrained shear strength is the governing design criterion.

3.3. Triaxial UU (Soaked Condition)

In soaked (saturated) conditions, the undrained shear strength decreased compared to dry conditions but remained higher than untreated soil. The maximum Cu achieved at 3% xanthan gum was 1.09 kg/cm², while untreated soil had only 0.33 kg/cm². The internal friction angle (ϕ) also decreased from 6.12° (untreated) to 1.14° (3% xanthan gum). The lower strength in soaked samples is likely due to partial dissolution or softening of the xanthan gum network in water, which weakens the biopolymer-soil bonds.

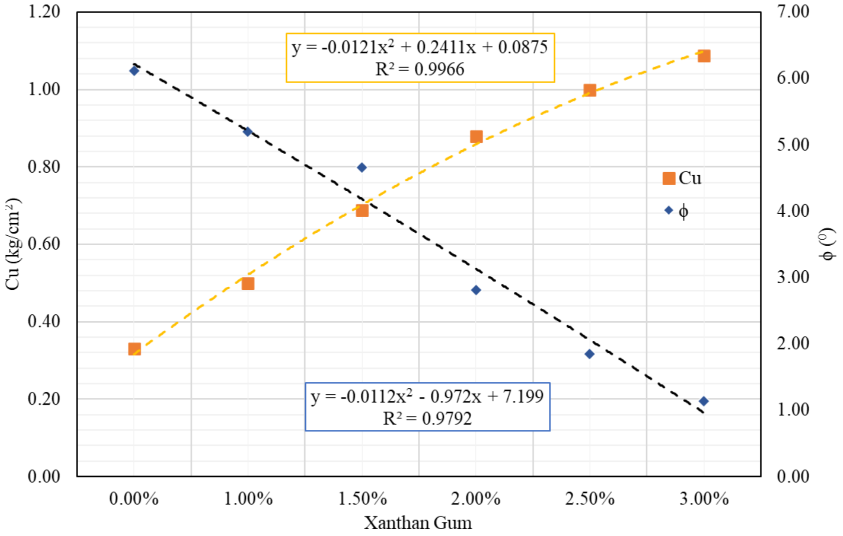


Fig. 7. Effect of xanthan gum content on cohesion (Cu) and internal friction angle (ϕ) of tropical residual soil under soaked conditions, as determined from UU triaxial tests.

Although a substantial reduction in cohesion (Cu) was observed under soaked conditions compared to dry testing, xanthan gum still provided a notable contribution to shear strength retention. In the current study, the maximum Cu at 3% xanthan gum reached 1.09 kg/cm², representing a considerable improvement over untreated soil (0.33 kg/cm²). This finding indicates that the polymeric structure formed by xanthan gum is capable of maintaining interparticle bonding even in a fully saturated state, although the strength achieved remains lower than in dry conditions (8.00 kg/cm² at the same xanthan gum content).

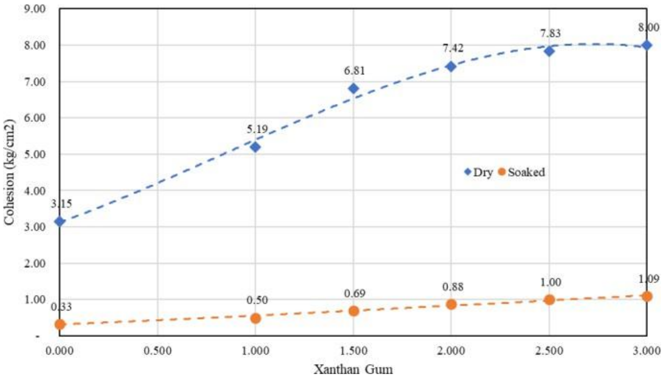


Fig. 8. Variation of soil cohesion with xanthan gum content under dry and soaked conditions for residual lateritic soil.

The reduction in triaxial test results observed in this study was far more severe than that reported by (16) for clayey soils treated with xanthan gum. While both studies demonstrated that xanthan gum improves Cu in soaked conditions compared to untreated samples, the residual lateritic soil in the current study experienced a sharper decline after saturation, indicating greater susceptibility to strength loss upon full saturation. This pronounced reduction is attributed to partial dissolution or softening of the biopolymer network in water, combined with the loss of matric suction, which plays a critical role in the shear strength and bearing capacity of lateritic soils in tropical regions. Under such conditions, fluctuations in moisture content and intense rainfall can cause significant degradation of soil structure despite its apparent strength in dry states.

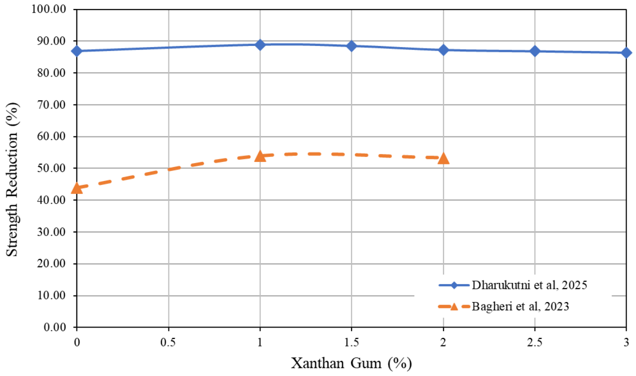


Fig. 9. Percentage reduction in shear strength after soaking.

3.4. Permeability Test

The addition of xanthan gum resulted in a pronounced decrease in the permeability coefficient of the soil. The permeability dropped from 2.64 × 10^{-6} cm/s (untreated) to 1.94 × 10^{-7} cm/s at 3% xanthan gum, a reduction of over 92%. This decline is attributed to the formation of a dense biopolymer matrix that fills and seals the soil pores, restricting water flow.

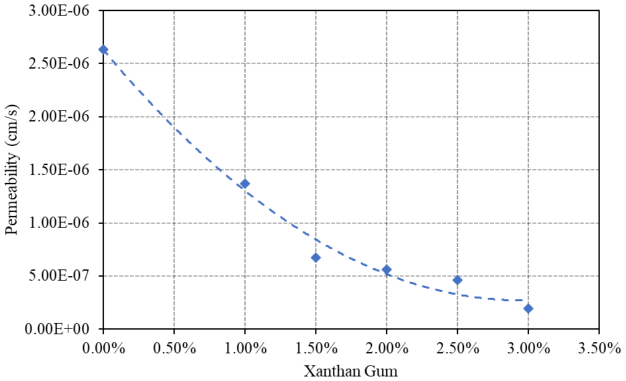


Fig. 10. Effect of xanthan gum content on the permeability of tropical residual soil.

This result corroborates findings by (7,9), who reported similar reductions in permeability when using xanthan gum as a soil stabilizer. The ability of xanthan gum to lower permeability is particularly advantageous in tropical soils, where reducing water movement is critical for slope stability and the prevention of soil erosion.

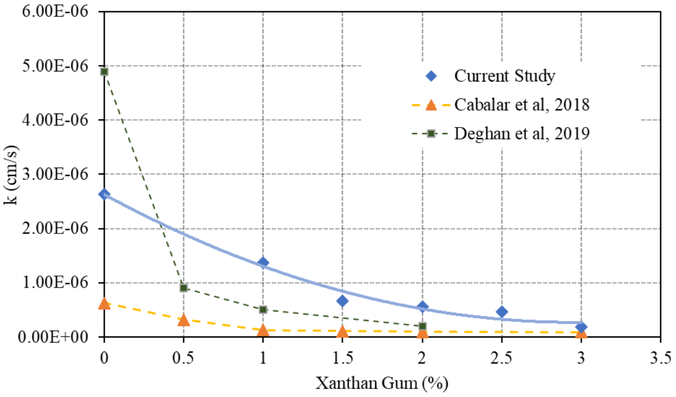


Fig. 11. Effect of xanthan gum content on soil permeability (k) for residual lateritic soil (current study) compared with previous studies on clayey soils.

3.5. Potential Limitations and Challenges

While xanthan gum has demonstrated considerable potential in improving the mechanical properties of tropical residual soils, several factors may limit its long-term performance and field applicability. One of the primary concerns is the substantial reduction in strength under soaked conditions. The pronounced loss in both unconfined compressive strength (UCS) and undrained shear strength (Cu) after saturation suggests that lateritic soils stabilized with xanthan gum are particularly susceptible to moisture-induced degradation.

Another challenge is swelling and shrinkage potential, as indicated by the progressive increase in both Plasticity Index (PI) and Liquid Limit (LL) with higher xanthan gum content. Based on (20) classification, soils with PI above 35% fall into the *very high* swelling potential category. The residual lateritic soil in the current study exceeds this threshold at xanthan gum contents above approximately 2%, indicating a considerable risk of volumetric instability.

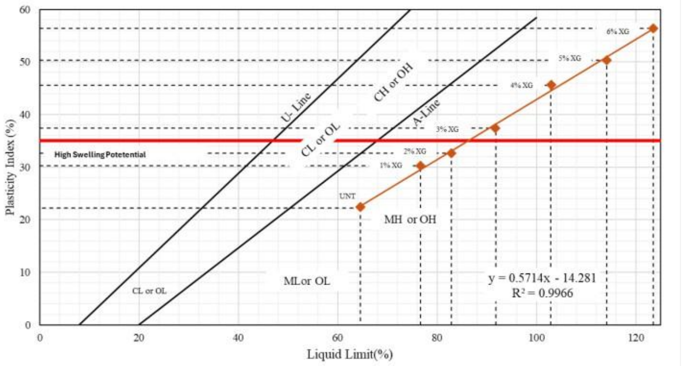


Fig. 12. lasticity Index vs. Liquid Limit for xanthan gum–treated lateritic soil.

Compared to (16), who studied clayey soils, the LL and PI increases observed in the present study are substantially greater, suggesting that lateritic soils have a stronger sensitivity to xanthan gum addition in terms of Atterberg limits. This elevated PI and LL correspond to a very high swelling potential according to Chen's criteria, which implies a greater susceptibility to moisture-induced expansion and shrinkage. In practical applications, such behavior can lead to significant challenges for infrastructure sensitive to volume change, such as pavements, light building foundations, and slope protection works, especially in tropical regions with pronounced wet–dry cycles.

4. CONCLUSIONS

This study has demonstrated the technical feasibility and effectiveness of xanthan gum as a soil stabilizer for tropical residual soils. The experimental results provide new insights into the mechanical and hydraulic behavior of xanthan gum-treated soils under both dry and soaked conditions. The following key conclusions highlight the main contributions and significant findings of this research:

1. The addition of xanthan gum to tropical residual soils leads to a marked increase in both unconfined compressive strength (UCS) and undrained shear strength, with the highest performance consistently

achieved at a 3% dosage. Notable strength enhancements are also evident at lower dosages of 1% and 1.5%.

2. Xantan gum treatment remains effective even under soaked conditions, with stabilized soils retaining higher strength compared to untreated samples, demonstrating its robustness in fluctuating moisture environments.
3. The treatment significantly reduced soil permeability, achieving more than 90% reduction in the coefficient of permeability at 3% content, indicating potential benefits for seepage control.
4. Plasticity Index (PI) increased with higher xanthan gum content, with certain dosages falling within the high swelling potential category. This suggests a greater risk of swelling and shrinkage, which must be considered in applications sensitive to volumetric changes.
5. The research provides new empirical data and practical insight on dosage optimization, emphasizing that careful selection of xanthan gum content is critical to realizing maximum benefits in ground improvement projects.

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