Numerical Simulation and Laboratory Evaluation of Xanthan Gum for Stabilizing Tropical Residual Soils

Salim Abdul Hakim[1*], Herwan Dermawan[1], Rakhmat Yusuf[1]
[1]Civil Engineering Study Program, Indonesia University of Education
*Corresponding Author: Salim Abdul Hakim. Email: abdulhakimsalim45@gmail.com

Abstract

This study investigates the effectiveness of Xanthan Gum (XG), a natural biopolymer, in improving the geotechnical properties of tropical residual soils through laboratory testing and numerical simulation. A series of Unconfined Compression Tests (UCT), permeability tests, and Triaxial Unconsolidated Undrained (UU) tests were conducted on soil samples treated with varying XG contents (0%–3%). The results showed that increasing XG content enhanced soil strength parameters, reduced permeability, and significantly improved cohesion. These laboratory findings were incorporated into PLAXIS 2D finite element modeling to evaluate slope stability under different rainfall scenarios. The simulations demonstrated that a minimum of 1.0% XG was sufficient to raise the Factor of Safety (FoS) above 1.5, the common threshold for slope stability, even under heavy rainfall conditions. Moreover, soil displacement decreased by up to 33% with increasing XG content. An optimal XG 2.0% was identified, offering a balance between performance and efficiency. The study concludes that xanthan gum is a viable and eco-friendly alternative for stabilizing residual soils in infrastructure applications.

Keywords: Xanthan Gum, residual soil, soil stabilization, slope stability, biopolymer

1. INTRODUCTION

Residual soils are formed in place through the weathering of parent rocks, without being transported [1]. In Indonesia, these soils are commonly found in hilly and mountainous regions, where high rainfall and steady temperatures accelerate the weathering process [2] [3]. However, tropical residual soils often have unstable and variable geotechnical properties, which can cause problems for slope stability and subgrade support in construction [4].

To improve soil performance, stabilization methods are often used. Cement is a common stabilizer, but its production causes high CO_2 emissions [5] [6]. As a more eco-friendly alternative, biopolymers like xanthan gum are gaining attention. Studies show that adding xanthan gum can improve soil strength by increasing cohesion and internal friction angle [7] [8] [9]. This happens because xanthan gum forms a gel-like matrix that binds soil particles and retains moisture, making the soil denser and more resistant to erosion and shrinkage [9] [10] [11].

This study investigates the effect of xanthan gum on tropical residual soils through laboratory tests, including Unconfined Compressive Test (UCT), Triaxial UU test, and permeability tests using the falling head method. The results are also compared with numerical simulations to validate the model's reliability. Overall, this research highlights xanthan gum's potential as a sustainable soil stabilizer, especially in tropical climates where rainfall can cause soil instability.

1.1. Residual Soil

Residual soil is a type of soil that forms directly in place from the weathering of parent rock, without being moved from its original location. This process involves physical, chemical, and biological weathering over a long period [1]. These soils typically develop just above the bedrock and show signs of intense mineral breakdown [12]. Tropical residual soils often have a reddish to brownish color due to laterization a process that removes many original minerals and leaves behind iron and aluminum oxides, as well as secondary clay minerals like kaolinite [7].

1.2. Xhantan Gum

Xanthan gum is a polysaccharide made by fermenting *Xanthomonas campestris* bacteria, and is widely used as a thickening agent. It has anionic, hydrophilic, and pseudo-plastic properties, which allow it to increase water viscosity significantly [13]. When applied to tropical residual soils, xanthan gum interacts with soil particles and affects their physical, mechanical, and hydraulic properties. The main stabilization process involves forming a polymer matrix that bonds with sesquioxide particles through electrostatic forces and hydrogen bonds [14].

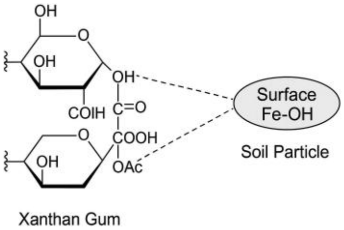


Figure 1. Chemical Bonding of Xanthan Gum with Residual Soil Particles

2. METHOD

The input parameters used in the simulation were obtained from laboratory test results and supported by secondary data on residual soils treated with xanthan gum. Model validation was carried out by comparing simulation outputs with experimental data to ensure consistency and accuracy. The analysis focused on slope stability, stress distribution, and deformation due to rainfall. This approach provides valuable insights into the effectiveness of xanthan gum as a soil improvement method under tropical conditions and contributes to the development of more sustainable ground stabilization strategies. All research materials, tools, and procedures for data collection, analysis, and interpretation were clearly defined.

2.1. Sample Collection

The lateritic soil samples for this research were collected from Rongga District, West Bandung Regency (coordinates: 107°17'4.30"E, 6°59'53.97"S). Soil samples were taken from the site with a sample depth of 1-3 meters from the ground surface.

Figure 2. Location of Soil Data Collected (Rongga, West Bandung, Indonesia)

2.2. Sample Preparation

Soil samples collected from the field were transported to the laboratory for preparation and testing according to standard procedures to determine their index properties. The reddish color of the soil, rich in iron and aluminum oxides, suggests that it developed under hot and humid tropical conditions. Initially, the soil's natural moisture content was reduced by sun-drying the samples for four days. A series of laboratory tests was then performed to characterize the properties of the lateritic soil.

Once the basic properties were identified, the soil was mixed with xanthan gum (XG) at various concentrations of 1%, 1.5%, 2%, 2.5%, 3%, 4%, 5%, and 6% by dry weight. For comparison, untreated soil samples (without XG) were also prepared. A dry mixing method was used to ensure uniform distribution of the additive throughout the soil matrix. The treated soils were compacted and molded into cylindrical specimens measuring 36 mm in diameter and 72 mm in height. For the permeability test, compacted samples were placed into the falling head test apparatus and saturated before testing. All specimens were then cured for 14 days under standard laboratory conditions (approximately 24°C) to allow stabilization.

Figure 3. Sample Preparation

2.3. Experimentation

Soil properties testing includes grain size distribution test (sieve and hydrometer analysis), Atterberg limits (liquid and plastic limits), specific gravity (particle density), and standard compaction test.

Table 1. Reference standard for soil properties testing

Laboratory Test	Reference
Grain size distribution (sieve & hydrometer analysis)	ASTM D6923, ASTM D7928
Atterberg limit (liquid limit & plastic limit)	ASTM D4318
Specific gravity (particle density)	ASTM D854
Standard compaction test (standard proctor)	ASTM D698

Figure 4. Soil properties experimentation test

Furthermore, mechanical tests were conducted to evaluate the soil's strength and hydraulic behavior, including the Unconfined Compressive Strength (UCT) test, Unconsolidated Undrained (UU) Triaxial test, and permeability test using the falling head method. All variations of xanthan gum content were examined in the UCT to identify the optimal dosage, defined as the content that yields the highest compressive strength before any reduction occurs. This optimal xanthan gum content was then used in the subsequent UU triaxial and permeability tests.

Table 2. Reference standard for soil mechanical testing

Laboratory Test	Reference
Unconfined Compressive Test (UCT)	ASTM D2166
Triaxial Unconsolidated Undrained (TX UU)	ASTM D2850
Permeability test (falling head method)	SNI 03-6870:2002

2.4. Numerical Analysis

A slope is stable when resisting forces exceed driving forces that cause movement, with shear strength being a key factor. This strength is influenced by soil type, density, water content, and pore pressure. When driving forces surpass resistance, failure can occur. The Finite Element Method (FEM) is widely used in geotechnical engineering to model slope stability, accounting for stress-strain behavior, complex geometries, and varying load conditions.

The embankment model was designed to resemble the typical geometry of road construction in the field, and subsequently subjected to combined loading from both the pavement structure layers and traffic loads. The embankment model was constructed to resemble the geometry of an actual road construction at STA 3+550 of the Trans Sumatera Ruas Indrapura – Kisaran toll road project. The embankment was subjected to a combined load, consisting of a 10 kN/m² structural load based on the design data, and a 15 kN/m² traffic load, as referred to in the Geotechnical Guideline 4 No. Pt T-10-2002-B (2002).

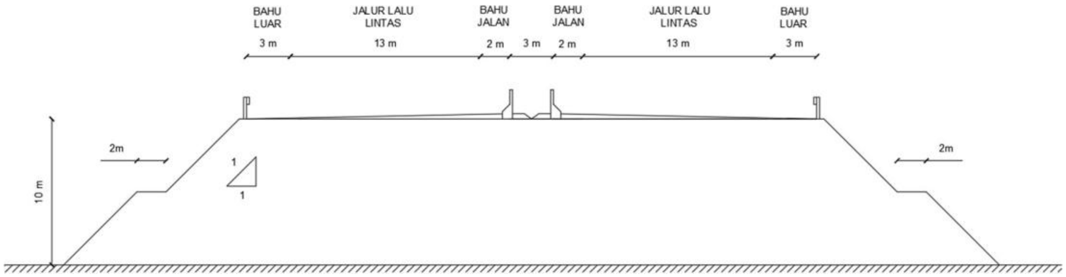


Figure 5. Embankment model

Table 3. Subgrade soil parameter

Soil Type	Thickness (m)	γ_n (kN/m^3)	γ_{sat} (kN/m^3)	e0	C' (kN/m2)	ϕ	E (kN/m2)
Silty Clay	4	13.99	15.39	2.23	24.14	17.21	3000
Silty Clay	10	11.89	13.08	1.96	16.42	21.45	5865
Silty Sand	6	14.35	15.78	1.16	53.04	34.29	50000
Silty Sand	10	14.35	15.78	0.89	36.22	44.59	69000

The variation in rainfall intensity in this simulation refers to the classification system established by the Meteorology, Climatology, and Geophysics Agency (BMKG), representing light to very heavy rainfall conditions commonly observed in tropical regions.

Table 4. Rainfall intensity

Rainfall Intensity	
Light Rainfall	0,1 – 5,0 mm/hr
Medium Rainfall	5 – 10 mm/hr
Heavy Rainfall	10 – 20 mm/hr

3. RESULT AND DISCUSSION

3.1. Physical Properties of Soil

The initial stage of this study involved laboratory testing to determine the basic physical properties of tropical residual soil.

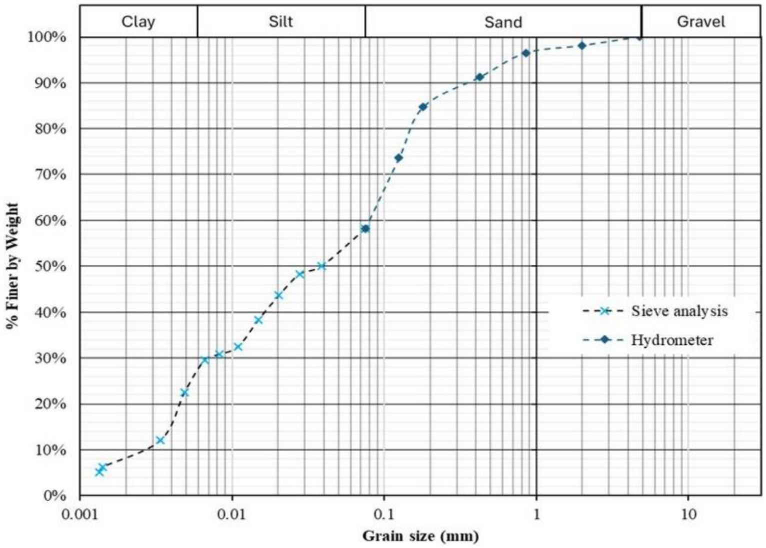


Figure 6. Particle-size distribution curves of soil

Table 5. Physical properties of soil

Soil Properties	Value
Specific Gravity	2.63
Liquid Limit (%)	64.55%
Plastic Limit (%)	42.00%
Plasticity Index (%)	22.55%
OMC (%)	37.00%

Based on the Atterberg limits test, the soil exhibits a Liquid Limit of 64.5% and a Plastic Limit of 42%, resulting in a Plasticity Index of 22.5%. When plotted on the plasticity chart, these values fall below the A-line, indicating that the soil is classified as inorganic silt with high plasticity (MH) according to the Unified Soil Classification System (USCS). Furthermore, with more than 50% of the particles passing the No. 200 sieve, the soil is categorized as fine-grained. MH soils typically have low swelling potential but are compressible and possess very low permeability.

3.2. Mechanic Properties of Soil

After determining the physical properties, Unconfined Compressive Test (UCT), Triaxial Unconsolidated Undrained (TX UU), and permeability tests were conducted to evaluate changes in shear strength and water flow behavior due to xanthan gum addition.

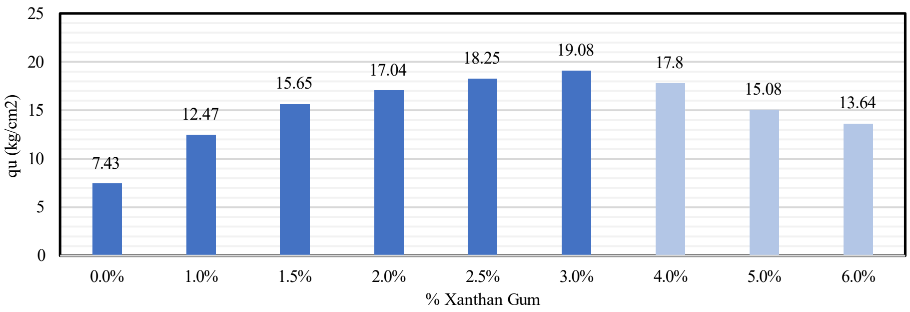


Figure 7. Unconfined Compressive Strength trends

The Unconfined Compressive Test (UCT) results show a significant increase in soil strength with the addition of xanthan gum, reaching a peak value of 1907.98 kN/m² at 3% concentration. Beyond this point, strength decreases, indicating an optimal dosage limit. The decline at 4–6% is attributed to overstabilization, where excessive xanthan gum disrupts particle bonding. Therefore, the xanthan gum concentrations used for the Triaxial Unconsolidated Undrained (TX UU) test were 1%, 1.5%, 2%, 2.5%, and 3%.

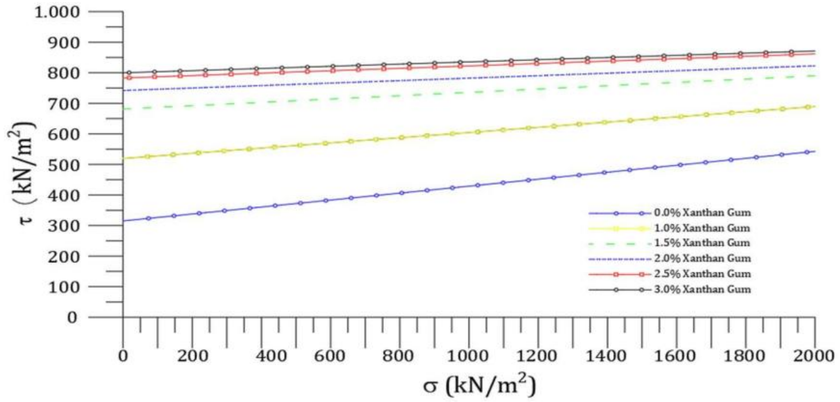


Figure 8. TX UU Mohr-Coulomb model

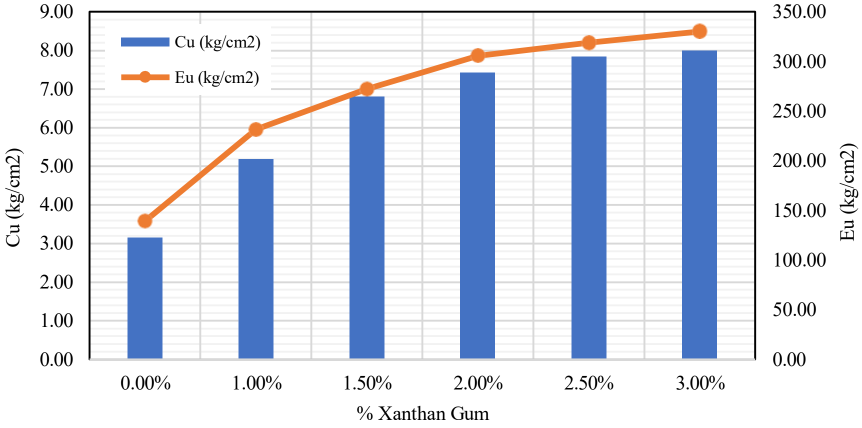


Figure 9. Cohesion & modulus young trend

The addition of Xanthan Gum to remolded soil samples significantly influenced the soil's shear strength parameters, particularly the undrained cohesion (Cu). A consistent increase in Cu was observed as the xanthan gum content increased. Without XG, the Cu value was recorded at 315.04 kN/m², rising to 519.46 kN/m² at 1% XG and reaching 799.72 kN/m² at 3% XG. This trend indicates that xanthan gum enhances interparticle bonding through gel network formation, thereby improving the soil's resistance to shear under undrained conditions. As a hydrophilic biopolymer, XG fills pore spaces and absorbs moisture, reducing interparticle friction and shifting the dominant strength mechanism from frictional to cohesive. Overall, the incorporation of xanthan gum contributes to significant strength improvement, particularly through increased undrained cohesion.

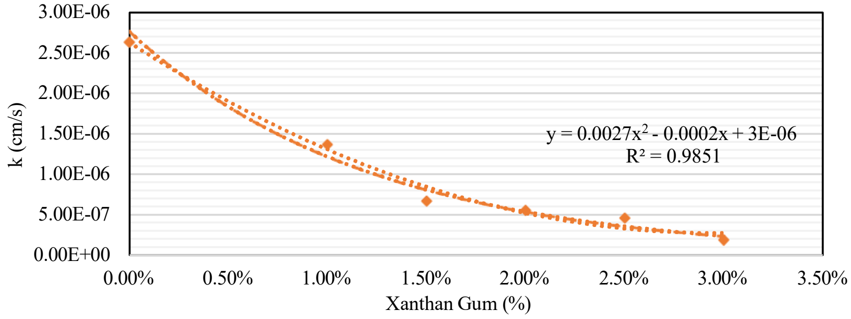


Figure 10. Permeability coefficients

The permeability coefficient (k) of the remolded soil decreases significantly with increasing xanthan gum content. Initially measured at approximately 2.6 × 10^{-6} cm/s without XG, the value drops to below 5.0 × 10^{-7} cm/s at 3% XG. This trend indicates that xanthan gum effectively reduces soil permeability by filling pore spaces and forming a viscous gel matrix, which obstructs water flow. The stabilization effect is particularly notable beyond 1.5% XG, where the permeability reduction becomes more gradual. This behavior supports the potential of xanthan gum as a sustainable permeability-reducing agent in geotechnical applications.

3.3. Finite Element Analysis

The simulation focuses on tropical residual lateritic soil that has been engineered by adding an additive material, Xanthan Gum (XG), with soil parameter variations obtained from laboratory test results.

Table 6. Soil parameter input

	y_n (kN/m3)	y_{sat} (kN/m3)	e0	Su (kN/m²)	E' (kN/m²)	k (m/d)
XG 0%	17.16	17.22	0.98	315.04	8348.38	2.28.E-03
XG 1%	15.47	16.48	1.21	519.46	13883.77	1.18.E-03
XG 1.5%	15.27	16.39	1.24	681.30	16337.66	5.81.E-04
XG 2%	15.04	16.29	1.27	741.96	18352.20	4.84.E-04
XG 2.5%	14.74	16.17	1.32	783.03	19134.38	4.01.E-04
XG 3%	14.69	16.14	1.32	799.72	19815.92	1.67.E-04

The soil parameters listed in Table 6 were used as material inputs for PLAXIS 2D simulations to model the behavior of XG-stabilized residual soils. These inputs, derived from laboratory tests, represent both mechanical and hydraulic characteristics necessary for analyzing slope stability and deformation under varying rainfall conditions. This ensured that the numerical model closely reflected the improved soil behavior due to biopolymer treatment.

Table 7. Result of safety factor slope stability using PLAXIS 2D

% XG	Factor of Safety			
	Without Rainfall	Light (<5 mm/h)	Medium (<10 mm/h)	Heavy (>10 mm/h)
0.00%	1.461	1.407	1.395	1.394
1.00%	1.730	1.692	1.675	1.675
1.50%	1.752	1.708	1.693	1.692
2.00%	1.777	1.729	1.715	1.713
2.50%	1.810	1.759	1.744	1.744
3.00%	1.814	1.766	1.745	1.744

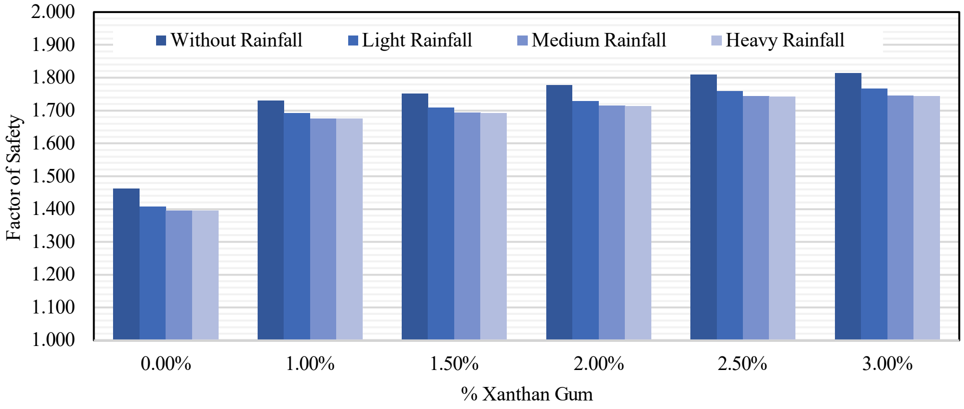


Figure 11. Result of safety factor slope stability using PLAXIS 2D

The results presented in the table illustrate the influence of varying Xanthan Gum (XG) content on the Factor of Safety (FoS) of embankment slopes under different rainfall conditions. Without any XG (0.00%), the FoS values are consistently below the minimum safety threshold of 1.5 across all scenarios, indicating a potential risk of instability, particularly during rainfall. With the addition of 1.00% XG, the FoS increases significantly and exceeds 1.5 in all conditions, including during heavy rainfall, where it reaches 1.675. This demonstrates that even a small percentage of XG can substantially enhance slope stability. Further increases in XG content (1.50%–3.00%) lead to progressively higher FoS values, although the rate of improvement begins to plateau beyond 2.00%, suggesting diminishing returns relative to the additional material required. At 3.00% XG, the FoS peaks at 1.814 without rainfall and remains high at 1.744 under heavy rainfall. These findings indicate that all mixtures containing 1.00% XG or more are sufficient to ensure stability, but the range of 1.50% to 2.00% offers an optimal balance between safety and efficiency, particularly in regions susceptible to moderate to heavy rainfall.

Table 8. Result of slope stability displacement using PLAXIS 2D

%XG	Displacement (cm)			
	Without Rainfall	Light (<5 mm/h)	Medium (<10 mm/h)	Heavy (>10 mm/h)
0.00%	8.797	9.697	10.270	10.400
1.00%	6.947	7.714	7.777	7.785
1.50%	6.567	7.269	7.298	7.309
2.00%	6.270	6.951	6.971	7.006
2.50%	6.159	6.768	6.819	6.836
3.00%	6.075	6.591	6.595	6.786

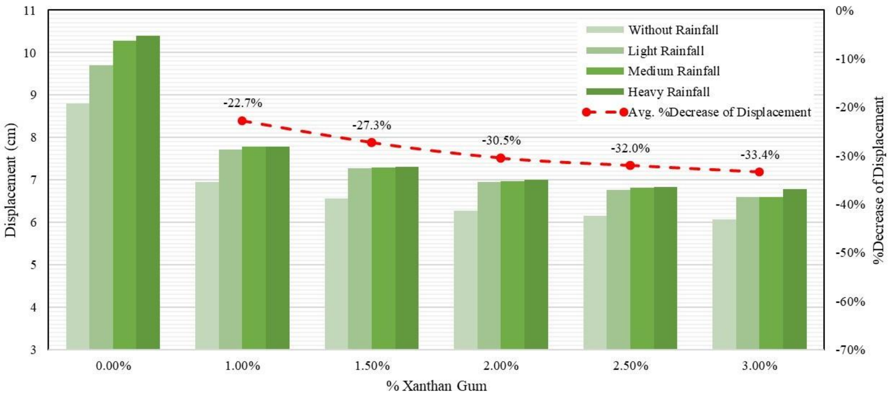
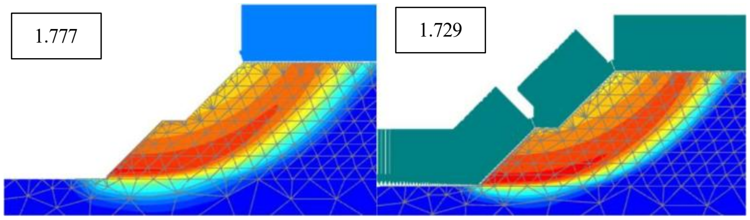
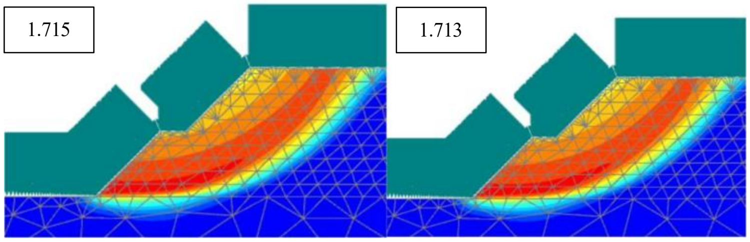


Figure 12. Result of slope stability displacement using PLAXIS 2D

The displacement results obtained from PLAXIS 2D simulations show a clear trend of decreasing slope deformation with increasing Xanthan Gum (XG) content, across all rainfall conditions. Without the addition of XG (0.00%), displacement reaches its highest values, particularly under heavy rainfall (10.400 cm). As the XG content increases to 1.00%, displacement reduces substantially in all conditions, with a noticeable 22.7% average decrease. Further increments in XG percentage continue to lower displacement, reaching a maximum reduction of approximately 33.4% at 3.00% XG. This trend confirms the effectiveness of XG as a soil stabilizing agent in reducing deformation, even under adverse hydrological conditions. The displacement decreases most rapidly between 0.00% and 2.00%, beyond which the rate of reduction slows, indicating a point of diminishing returns. Overall, the use of XG contributes significantly to the stability of embankments by minimizing displacement, with optimal efficiency observed 2.00% XG content.



(Without Rainfall) (Light Rainfall)



(Medium Rainfall) (Heavy Rainfall)

Figure 13. Slope failure area.

4. CONCLUSIONS

This study evaluates the effectiveness of xanthan gum (XG) as a sustainable soil stabilizer for tropical residual soils through a combination of laboratory testing and finite element simulation. The following key conclusions are drawn:

1. Laboratory tests revealed that the addition of xanthan gum significantly enhances the mechanical

properties of tropical residual soils. The unconfined compressive strength and undrained cohesion (Cu) increased with higher XG content, with an optimal range identified at 2–3% before strength began to decline due to overstabilization.

2. Permeability tests showed a notable reduction in the coefficient of permeability with increasing XG content, reaching an order of 10^{-7} cm/s at 3% XG. This indicates that xanthan gum effectively reduces water flow through the soil matrix by filling pore spaces and forming a gel-like barrier.
3. Finite element simulations using PLAXIS 2D demonstrated a significant increase in Factor of Safety (FoS) with xanthan gum stabilization. A minimum XG content of 1.0% was sufficient to achieve FoS values greater than 1.5 under all rainfall scenarios, meeting common geotechnical safety requirements. The FoS peaked at 1.814 in dry conditions and remained above 1.74 under heavy rainfall with 3.0% XG.

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