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The effectiveness of bio-anchorage system in reinforcing tropical residual slope

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Abstract. Geotechnical phenomena known as “land sliding” encompasses a broad spectrum of ground movements, including rock falls, deep slope failures, and shallow debris flows, particularly in tropical regions. The severity of this issue is higher in regions with a lot of residual soils, like Malaysia, due to the frequent and intense rainfall events and the unique soil properties that make these areas prone to instability. The use of vegetation in soil bioengineering has gained attention recently as an environmentally friendly technique for stabilizing slopes, as most conventional approaches are neither inexpensive nor universally accessible. The primary objective is to understand the bioinspired soil anchoring system’s interaction mechanism to improve the bonding between the residual soil structure in tropical regions. This research is conducted to determine the relationship between the tensile strength of *Eugenia Oleina* plant roots and the soil parameters of Gambang residual soil. Laboratory testing for soil properties and classification procedures were conducted. Root tensile strength, compressive strength, and shear strength were determined by conducting an unconfined compression test and a direct shear test. These tests are crucial in understanding the mechanical properties of the soil and how it interacts with plant roots under different stress conditions. The comparison between *Eugenia Oleina* (EO) and *Dicranopteris Linearis* (DL) plant roots was obtained to recommend the best plant roots for slope stabilization. Out of all the bioinspired soil anchoring systems for tropical slopes, the findings offer the best answer. Thus, it was determined and suggested which plant species would be the most effective tool in residual soil to reinforce tropical slopes.

Introduction

In response to an ever-increasing landslides case, there is an urgent need to develop more effective erosion mitigation and landslide prevention strategies. In the past, researchers have investigated the use of vegetation to improve slope stability and reduce soil erosion. However, their collective efforts on the developed data collection and modelling techniques are not fully understood on the root-soil interactions at different bio-loading scales especially in tropical region where large amount of residual soil exist. In Malaysia for example, changes in land use have inevitably involved in removing of vegetation cover and cutting of hill slopes which has affect soil properties and environment [1]. High intensity and more frequent rainstorms, lack of suitable species on hilly areas and conventional planting techniques such as hydro seeded grasses have been identified as the main cause for frequent landslides [2]. The removal of vegetation disrupts the natural stability provided by root systems, making slopes more susceptible to erosion and failure. Reinforcement of slope using eco-friendly approach is highly promising in reducing surface erosion and shallow landslides [3]. Hence, fundamental knowledge lack on how tropical plant roots interacts and bond with residual soil in Malaysia. Existing theories and mechanisms are based on foreign plants, and soils which did not reflect the local soil parameters and climatic condition.

Acharya et al. [4] stated that the rise in the production usage of conventional material especially in slope stabilization has caused a lot of environmental disruptions due to releasing the harmful gases. Conventional construction materials have caused the rise of greenhouse, emissions of harmful gases, and global warming. Incorporating sustainable and environmentally friendly methods in engineering practices is crucial for reducing the carbon footprint and mitigating adverse environmental impacts. Civil engineers have the difficult challenge of eliminating conventional materials to make the environment more sustainable. Engineers were required to brainstorm various creative alternatives for ground improvement in collaboration with researchers.

According to Noorasyikin & Zainab [5], the bioengineering technique which is vegetation cover was usually applied for mitigation of slope failure because of its advantages. The technique is less costly, fast grows, and is easily planted. Generally, the vegetation mainly stabilizes the slope by mechanical effects through the root matrix system [6]. The root matrix system provides additional shear strength to the soil, reducing the likelihood of slope failure. Research conducted by Mukhsin [7] indicated that for the slope stability study, adequate plant selection is also required. In the past ten years, studies on root reinforcement have concentrated on a variety of topics, including qualitative descriptions of processes, experimentally derived quantitative estimates, the creation of theoretical models, and calculations of slope stability [8]. Understanding the specific root-soil interactions and the mechanical properties of different plant species is vital for designing effective bioengineering solutions for slope stabilization.

The main aim of this study is to investigate the properties of Gambang soil and the tensile strength of selected tropical plants which is *Eugenia Oleina* for slope stabilization. Additionally, it entails classifying and contrasting various plant species according to how well they can function as bio-anchors in selected site conditions. Duraisamy et al. [9] claimed that *Eugenia Oleina* has a growing rate of up to 1.2 meters per year and this rate is relatively faster than the rate found in other tropical plant species. The results of this study are crucial for improving our comprehension of how native plant roots interact with the remaining soil matrix in tropical regions. This will provide soil engineers with new and fresh insights into the workings of the bio-anchorage system, enabling them to select the appropriate plant species for landslip mitigation and slope protection projects in tropical regions.

Methodology

This research's study area was the Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) campus. The selected plant type already existed at the selected slope as shown in *Fig. 1*. The selection criteria were predicated on whether the species belonged to ferns or woody trees and if they had to have the necessary root structure. It is expected that the *Eugenia Oleina* trees that are currently in UMPSA are at least ten years old. The *Dicranopteris Linearis* plant can be found on slopes along the Gambang highway.

(a) (b)

Fig. 1 Study area at UMPSA Gambang campus (a) plan view (b) side view

Laboratory tests were performed on the collected samples at the Soil Mechanics & Geotechnical laboratory of UMPSA in Gambang Campus. The soil test was conducted through multiple tests, including moisture content, sieve analysis, hydrometer, Atterberg limit, particle density, and standard proctor test. The mechanical properties of the roots were determined through the execution of the unconfined compression test and direct shear test. Apart from that, the tensile strength of both roots was taken from past research papers. Field emission scanning electron microscopy with energy dispersive X-ray spectroscopy analysis (FESEM with EDX) was carried out to display the image of the topography surface of selected plant roots.

The summary of the laboratory test that was carried out is listed in Table 1. All tests were carried out in accordance with American Society for Testing and Material (ASTM) except for FEDEM with EDX.

Table 1 Summary of laboratory tests

Laboratory test	Code of Practice
Sieve Analysis	ASTM D422
Moisture Content	ASTM D2216
Particle Density	ASTM D854
Hydrometer	ASTM D422
Atterberg Limits	ASTM D427 & ASTM D4318
Direct Shear Box	ASTM D3080
Unconfined Compressive Strength Test	ASTM D638
Standard Proctor Compaction Test	ASTM D698
FESEM with EDX	-

Results and Discussions

Soil Classifications. The primary soil properties which are the liquid limit (LL), plasticity index (PI), coefficient of uniformity (Cu), and coefficient of gradation (Cc) are obtained using sieve analysis and Atterberg limit test to classify the soil. Classifying soil allows for an understanding of its behaviour and a direct correlation between its mechanism of interaction and the characteristics of tree roots. This classification is important for determining the suitability of soil for supporting plant growth and stability. Based on the results found that the soil moisture content in the selected area is in moderate condition and the plasticity index stated the soil sample has a low level of plasticity. It can be concluded that, the soil is classified as poorly graded sandy silt with low plasticity. Data obtained from the tests are presented in Table 2 and the sieve analysis graph as in *Fig. 2*.

Table 2 Summary of soil properties

Properties	Value
Liquid Limit (LL), %	45.80
Plasticity Index (PI), %	6.36
Coefficient of Uniformity (C_u)	5.89
Coefficient of Gradation (C_c)	1.30
Optimum Moisture Content %	17.60
Dry Density (g/m^3)	1.75

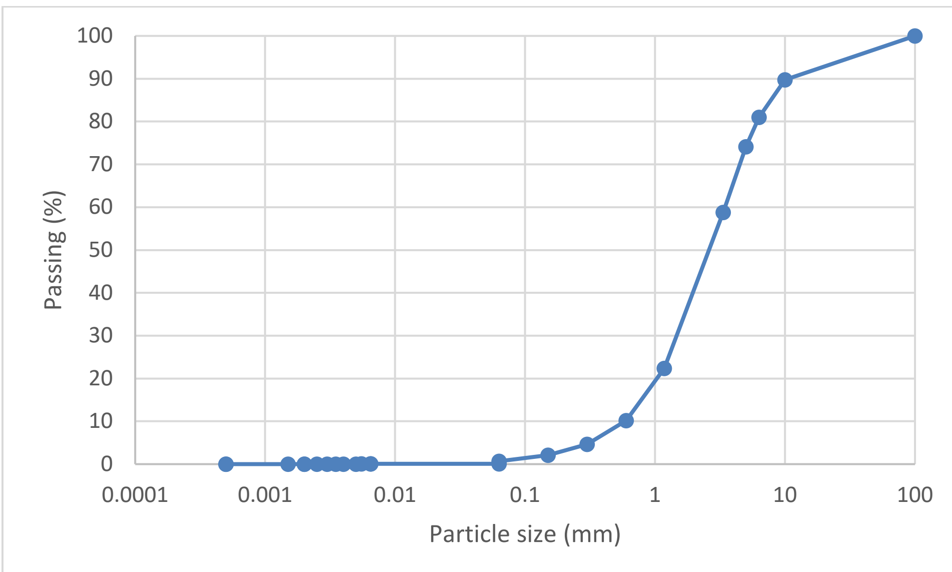


Fig. 2 Particle size distribution of Gambang residual soil

Tensile Strength. The tensile strength of roots refers to their ability to withstand pulling or stretching forces. High tensile strength roots upon breaking can increase slope stability since the soil can only withstand a relatively little displacement before rupturing. The tensile strength of *Eugenia Oleina* (EO) was taken from Duraisamy et al. [9] research paper as shown in *Fig. 3* and *Dicranopteris Linearis* (DL) plant roots from Zhou et al. [10] research paper.

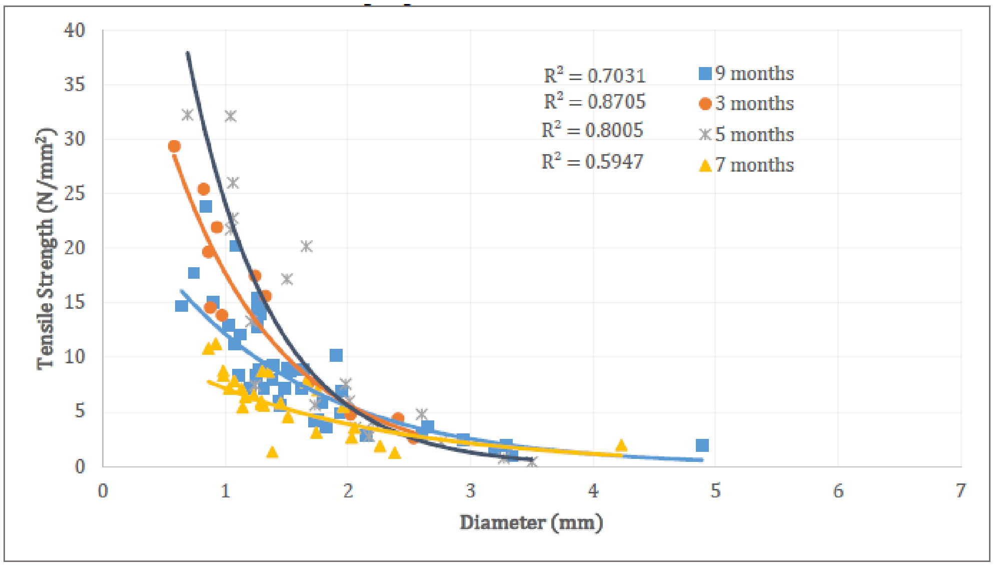


Fig. 3 Tensile strength and root growth differences of Eugenia Oleina

Based on the data presented in Table 3, the peak tensile strength of EO obtained is 32.20 Mpa and from Zhou et al. [10] journal, the highest tensile strength of DL was 8.79 Mpa.

Table 3 Tensile Strength of Eugenia Oleina and Dicranopteris Lienaris

Plant type	Tensile Strength (Mpa)
Eugenia Oleina (EO)	32.20
Dicranopteris Linearis (DL)	8.79

Unconfined Compression Strength (UCS) Test. The unconfined compression test is carried out to determine the compressive strength of unrooted and rooted samples. One of the important measures of a root's resistance to damage is its compressive strength, which contribute to the overall stability on slopes. Fig. 4 illustrates the bahaviour of the two dissferent root species and the sizes towards compressive force. Following that Table 4 with the summary of UCS results are reported to show the trend in behavior of root.

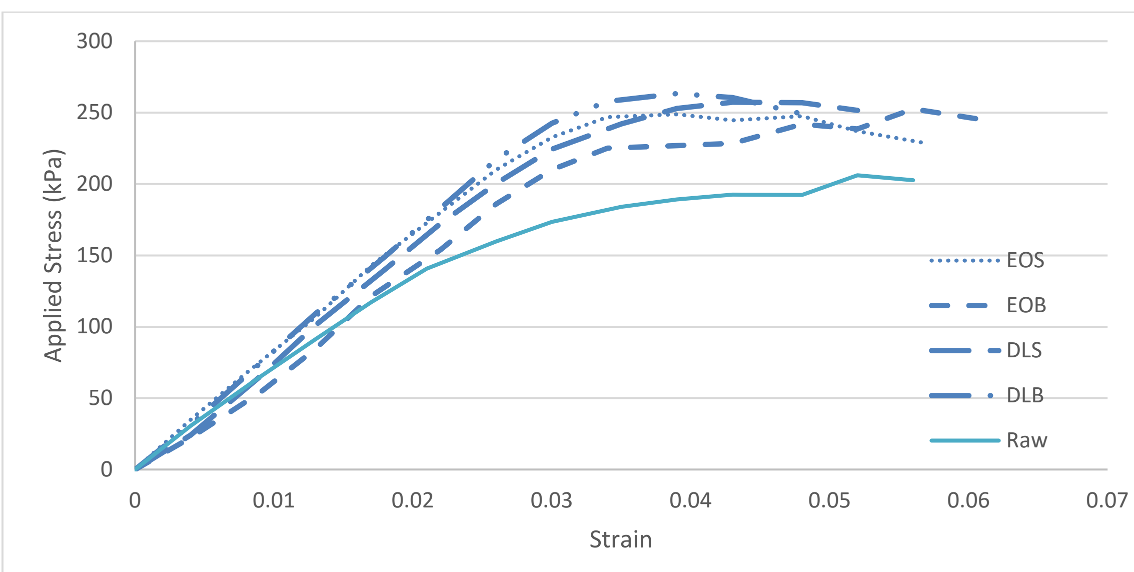


Fig. 4 Raw Sample Stress vs Strain

Table 4 UCS Results of Unrooted and Rooted sample

Sample Type	UCS (kPa)
Unrooted (Raw)	206.09
Eugenia Oleina (small), EOS	248.80
Eugenia Oleina (big), EOB	252.53
Dicranopteris Linearis (small), DLS	257.26
Dicranopteris Linearis (big), DLB	263.32

The compressive strength is compared with two types of plant roots and two different diameters of roots. The diameters are in the range of 1 mm to 3 mm for smaller roots and 3 mm to 5 mm for bigger roots. By comparing both roots, the peak compressive strength is obtained from the soil with big *Dicranopteris Linearis* roots. The compressive strength of *Eugenia Oleina* increases when the diameter of the roots gets bigger.

Direct Shear Box Test. The shear strength of a plant is an important factor in engineering applications, particularly for slopes. In cases where shear stresses are resilient, a plant with a higher shear strength is often desirable since it suggests better resistance to shear deformation and failure.

The results presented in *Fig. 5* show that shear strength for unrooted dry soil is higher compared to rooted soil samples. The bonding between soil and roots is not achieved due to the dried soil. Based on a comparison between both roots, the *Eugenia Oleina* trees has higher shear strength compared to the *Dicranopteris Linearis* plant.

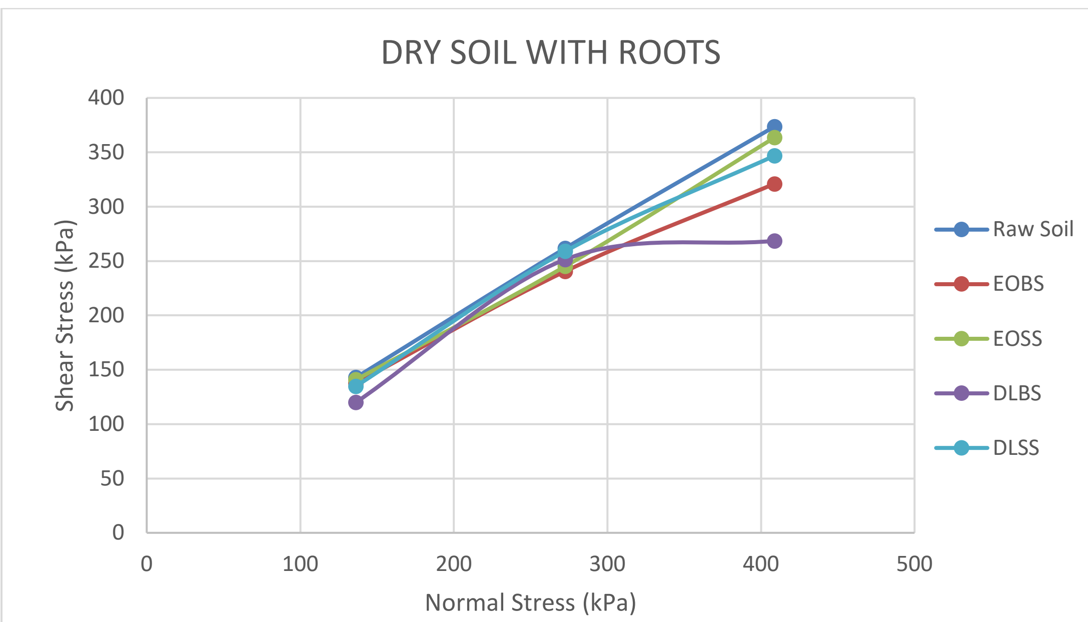


Fig. 5 Shear stress vs Normal Stress of Dry Soil with roots

The results presented in *Fig. 6* show that the shear strength for rooted wet soil is higher than for unrooted soil samples. Based on a comparison betwen both roots, the small *Eugenia Oleina* root has higher shear strength compared to *Dicranopteris Linearis* root. The shear strength increases when the load is increased for unrooted and rooted samples, but comparatively, these two types of plant roots have a significant contribution to shear strength on the slope in wet conditions.

Based on the root analysis that has presented, the tensile strength of *Eugenia Oleina* is higher compared to *Dicranopteris Linearis* root. In contrast, the compressive strength of DL roots is larger than EO roots, meaning that DL can bear more compressive force before failing. On the other hand, the shear strength of EO root providing peak shear strength compare to DL root, but in dry condition the unrooted soil is higher than rooted soil.

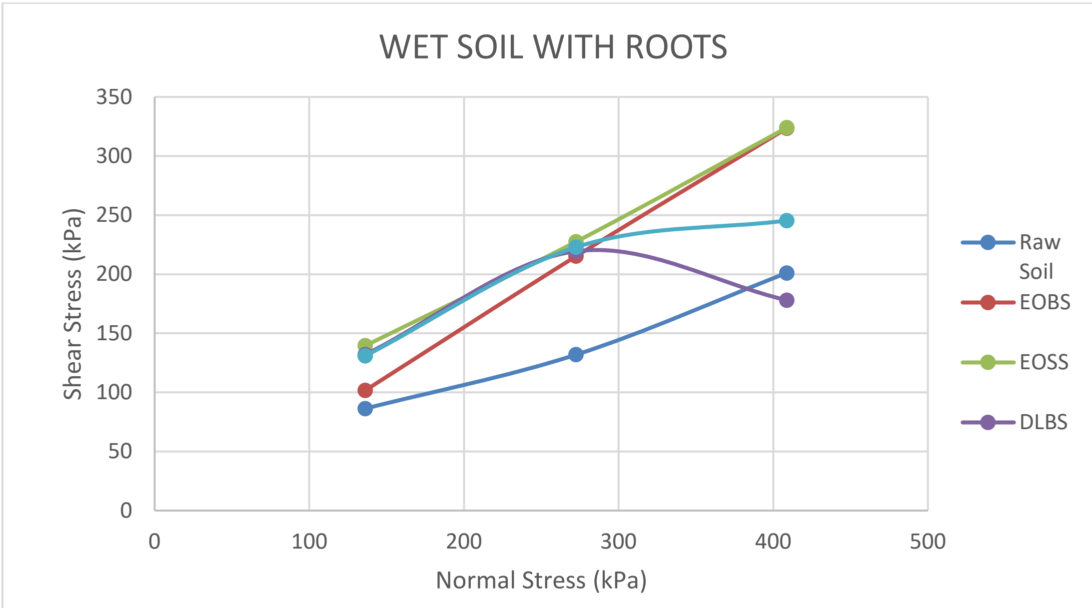
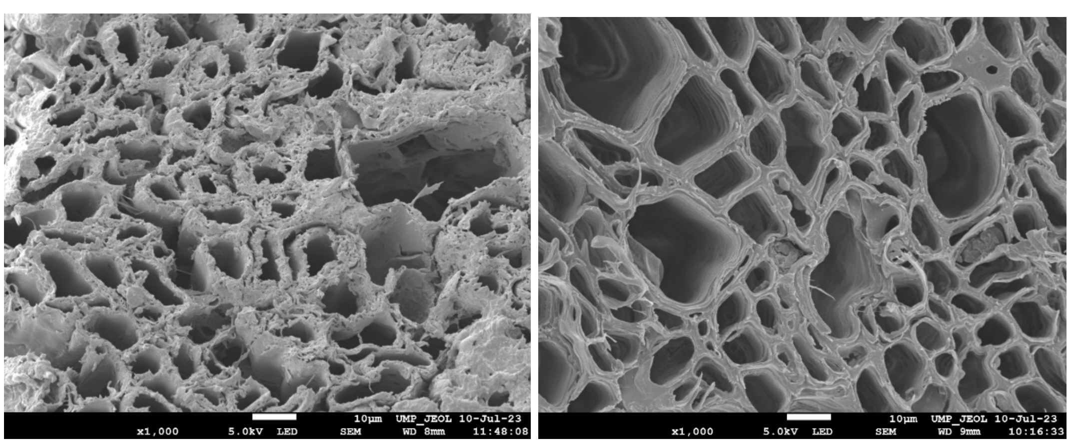


Fig. 6 Shear Stress vs Normal Stress of Wet Soil with Roots

The FESEM with EDX test was done to analyse the bisection of root samples. Out of multiple magnification captures, the best magnification, which is 1000x is selected to present the best view that can indicates the physical differences between maturity and type of plant. Throughout this research, many other factors were used and considered in determining the maturity of the plants. This particular test went another mile further to describe the root condition in a more detailed view. *Fig. 7* shows that horizontally bisected roots of younger and matured *Eugenia Oleina* whereas *Fig. 8* shows horizontally bisected roots of younger and matured *Dicranopteris Linearis*.



(a) (b)

Fig. 7 Horizontal roots bisection of (a) young and (b) matured Eugenia Oleina

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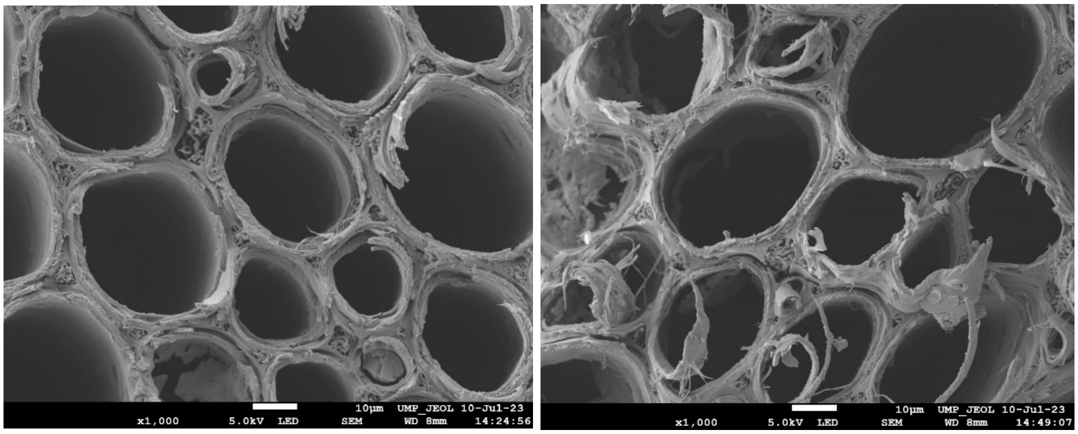

(a) (b)

Fig. 8 Horizontal roots bisection of (a) young and (b) matured Dicranopteris Linearis

As shown in *Fig. 7*, the growth of the roots of *Eugenia Oleina* is very obvious and drastic. It can be seen that the younger *Eugenia Oleina* has a very compacted area of the small and tiny xylems whereas the grown *Eugenia Oleina* has bigger xylems which can be seen less compacted. The thickness of the wall of the xylems seems to be the same. Therefore, it is justified to say that this research used *Eugenia Oleina* roots that belongs to two different age group.

The case is slightly different for *Dicranopteris Linearis*. Referring to *Fig. 8*, the growth of the roots of *Dicranopteris Linearis* does not seem to be significant. This is because, both the sample almost look the same in terms of how compacted the xylems are and the size of xylems. This might be due to the plant does not require large roots to withstand its own weight as it categorized as a fern type plant or tendrils. Therefore, it is a challenging task to differentiate the maturity of the plant from its roots bisection whereas it can be done by observing the area the plant covered in growing and the colour of leaves. Light green indicates younger plant and darker green indicates matured plant. The samples of roots of *Dicranopteris Linearis* was collected based in these two criteria.

Based on the observations and tests that have been conducted, some improvisations can made for further improvement. Experimenting with undisturbed specimens may help to preserve the natural characteristics of soil as found in the field. Understanding the root morphology and its behaviour in different enviromental conditions may lead the research to a better level and studying more about other type of plants such as shrubs and grasses can offer a comprehensive approach to soil stabilization. Different root structures within a diverse plant community contribute to various aspects of soil stability, such as binding and deep anchoring.

Conclusions

From this investigation, Eugenia Oleina exhibits the highest tensile and shear strength compared to *Dicranopteris Linearis.* This indicates that *Eugenia Oleina* can endure higher levels of tensile stress before failure occurs in tension. However, it is important to note that despite its high tensile and shear strength, *Eugenia Oleina*'s effectiveness diminishes with increasing root diameter, leading to potential failure due to the increased self-weight of the trees. This limitation makes *Eugenia Oleina* less suitable for Gambang soil properties, which may suggest its better application on flatter surfaces rather than sloped terrains.

Additionally, the study's results underline the need for careful plant selection in bioengineering applications for slope stabilization. While *Eugenia Oleina* offers high tensile and shear strength, the overall success of bio-anchorage systems depends on the compatibility of plant species with local soil conditions and environmental factors.

The research findings advocate for a broader approach to bioengineering solutions, considering diverse plant species beyond *Eugenia Oleina* and *Dicranopteris Linearis*. Incorporating various plants, such as shrubs and grasses, could provide a more holistic solution to soil stabilization. The diversity in root structures within a plant community can enhance different aspects of soil stability, including surface binding and deep anchoring. This support the notion that understanding root morphology and behavior under varying environmental conditions is crucial for designing effective bioengineering strategies.

Future research should explore the use of undisturbed soil specimens to better preserve the natural characteristics of the soil as found in the field. Additionally, further studies on other plant species, such as shrubs and grasses, can offer more comprehensive solutions for soil stabilization. This multi-faceted approach aligns with the findings from previous research who highlight the potential of bioengineering techniques in reducing surface erosion and preventing shallow landslides in tropical regions.

In conclusion, while *Eugenia Oleina* demonstrates high tensile and shear strength, its suitability for slope stabilization in tropical residual soils may be limited by its increasing self-weight with root diameter growth. Exploring a wider range of plant species and their interactions with local soil conditions will provide more effective and sustainable solutions for slope stabilization in tropical regions.

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