Proceedings of the ICBBG2025
2025 International conference on Bio-mediated and Bio-inspired Geotechnics
18-20 May, 2025 | Tempe, Arizona, USA
https://doi.org/10.53243/ICBBG2025-109

Enhancing Soil Stability with Biopolymers and Vegetation

Anish Lamsal, S.M. ASCE,[1] Mohammadhasan Sasar, Ph.D., Aff.M. ASCE,[2] and Sherif L. Abdelaziz, Ph.D., P.E., M. ASCE[3]

[1]M.S. Student, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061; anish100@vt.edu
[2]Post-doctoral Associate, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA 24061; msasar@vt.edu
[3]Associate Professor, The Charles E. Via, Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia, 24061; saziz@vt.edu

ABSTRACT

Soil erosion is a significant environmental challenge, and improving soil stability through sustainable methods is essential for long-term erosion control. Vegetation has been a traditional method for stabilizing soil, while recent advances highlight biopolymers as eco-friendly soil stabilizers to enhance soil shear strength and erosion control. This study investigates the combined effect of xanthan gum (XG) biopolymer at concentrations of 0.5% and 1.5% and vegetation on soil shear strength and grassroots growth. Shear strength was measured using a specially designed direct shear apparatus capable of testing under low normal stresses, simulating surface soils exposed to shallow instability and erosion forces. The results demonstrated that integrating biopolymers with vegetation significantly enhances soil stability and shear strength compared to using biopolymers alone. These findings underscore the potential of biopolymers, particularly when combined with vegetation, to provide long-term erosion control with improved effectiveness.

INTRODUCTION

Slope stability and erosion control are crucial for both natural and engineered landscapes. The shear strength of soil plays a vital role in this stability. Vegetation, particularly through its roots, plays an essential role in slope stabilization and erosion control. Plant roots contribute to soil stability by binding soil particles together, thereby reducing erosion and acting as a reinforcement that enhances the overall shear strength of the soil (Gyssels et al. 2003, Reubens et al. 2007). Roots entangle soil particles, preventing sediment transport and creating mechanical barriers that reduce soil and water movement (Abernethy et al. 2000, Li et al. 2011). Mechanically, roots enhance soil strength by providing tensile strength, frictional resistance, and adhesive bonding (Watson et al. 2000). The high tensile strength of roots further contributes to the cohesive strength of the soil, enabling the soil-root matrix to transfer shear stresses effectively (Ghestem et al. 2014). Tengbeh (1993) observed that clay and sandy clay loam soils experienced at least a 500% increase in shear strength with the effect of grass.

Traditionally, improving shear strength has relied on mechanical means or the addition of chemical agents like cement and lime which has adverse effects on the environment. While these treatments are effective, they also pose significant environmental concerns and inhibit root growth, limiting their potential to improve erosion resistance. As a result, the development of eco-friendly biopolymers has gained momentum. Biopolymers, derived from natural sources like plants and microorganisms, offer a sustainable alternative for soil improvement (Chang et al. 2015; Hataf et al. 2018). These biodegradable polymers enhance soil properties by improving cohesion between soil particles, increasing water retention, and supporting soil structure. In addition to their direct benefits for soil stability, biopolymers also play a crucial role in promoting vegetation growth. By improving soil water retention and structure, biopolymers create a more conducive environment for root development, leading to healthier and more extensive root systems (Schachtman et al. 1998). Some biopolymers contain high sugar content and essential nutrients like phosphate and nitrogen, which nourish plants and promote germination and growth (García-Ochoa et al. 2000). Wang et al. (2023) demonstrated that biopolymers could significantly enhance soil water retention capacity, correlating with better germination and vegetation growth. Despite their many benefits, biopolymers are biodegradable and may degrade over time (Hiraishi and Taguchi 2009), which can limit their long-term impact on soil mechanical properties. However, the enhancements in tensile strength and root development facilitated by biopolymers can counteract this degradation by boosting soil shear strength.

The synergistic effects of biopolymers and vegetation on soil mechanical properties, particularly shear strength, have not been extensively studied. This paper addresses this gap by examining the effects of xanthan gum, a representative biopolymer, on root growth and its impact on the shear strength of surficial soil. Ryegrass seeds were used for vegetation, and the study focused on the effects of xanthan gum at concentrations of 0.5% and 1.5% relative to the dry weight of soil, over a 6-week period. The research compared the shear strength of soil treated with xanthan gum and roots to that of untreated soil. The results demonstrated that while 1.5% XG enhanced root diameter while inhibiting root length growth, 0.5% XG boosted root length with a slight reduction in root diameter. Customized direct shear tests were conducted to investigate the role of biopolymer and plant roots in providing additional shear strength to a soil matrix. XG-treated samples with roots demonstrated a significant increase in shear strength compared to untreated samples.

MATERIALS AND METHODS

Pre-Germination Process. To prepare for planting, ryegrass seeds—known for their effectiveness in erosion control, flood management, and dust stabilization (Wang et al. 2023; Zhou et al. 2007)—were pre-germinated in water over 7 days. The seeds were organized into five groups of five seeds each. These groups were placed on water-moistened paper towels and arranged in a square formation with a side length of 25.4 mm (1 inch), positioning four groups at the corners and one in the center. This layout, derived from preliminary studies, was designed to minimize root entanglement.

Biopolymer Hydration and Sand Mixing Process. Before combining with the soil, Xanthan Gum (XG) gel was prepared. The process involved placing 300 g of de-ionized water into a commercial blender, to which XG was gradually added in increments of 2.5 grams. Each addition was blended for one minute before adding the next increment, continuing this procedure until the desired biopolymer concentration was achieved.

The sand used in this experiment was Acco Sand, which is categorized as well-graded sand with silt (SW-SM) according to the Unified Soil Classification System. The hydrated biopolymer gel was mixed with 2000 g of washed Acco Sand using an 8-quart heavy-duty commercial stand mixer (KitchenAid KSM8990ER NSF-certified commercial stand mixer) with a standard Flat Beater. The blending process lasts 30 minutes per batch to ensure the correct amount of soil was prepared. After mechanical mixing, the biopolymer-sand mixture underwent an additional five minutes of manual mixing to guarantee uniform distribution. The prepared mixture was then portioned by mass into separate containers for compaction. 0% XG samples, consisting of sand mixed only with water, were prepared following an identical procedure. The treatments employed in this study are detailed in Table 1. Three samples were prepared for each of the considered treatments.

Table 1: Summary of Treatments Used in the Study

Treatment No.	XG (%)	Treatment Age
1	0	Fresh
2	0.5	Fresh
3	1.5	Fresh
4	0	6 weeks
5	0.5	6 weeks
6	1.5	6 weeks

Soil Compaction and Cultivation Processes.

The under-compaction method described by Ladd (1978) was applied to compact the biopolymer-soil mixtures. The mixtures were compacted in containers measuring 220 mm in width and 580 mm in length, with the soil compacted in five layers, each 28.2 mm thick, to reach a total height of 141 mm. A 203.2 mm square tamper was used for the compaction process. After compacting all layers, 18 direct shear ring samplers (each with a diameter of 63.5 mm and a height of 25.4 mm) were positioned on the soil surface and pressed 5 mm into the soil to secure them in place. The soil within each sampler was then pushed down by 10 mm using 5-mm thick wooden sticks at predetermined seed locations. In each hole, one group of pre-germinated seeds (with roots trimmed to 10 mm for consistency) was planted. A schematic of the seed arrangement and cultivation box is provided in Figure 1. All samples (i.e., each circle shown in Figure 1b) were watered with a total of 6.5 ml of tap water, an amount chosen to match the average daily rainfall in the United States as reported in 2023 (National Centers for Environmental Information, 2023).

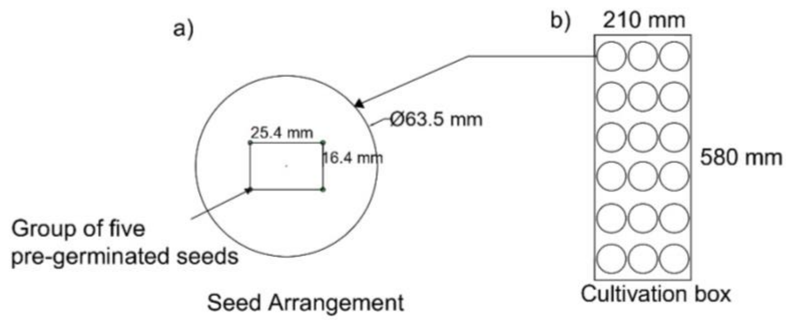


Figure 1. Diagram of seed arrangement (a), and depiction of the cultivation box used in the experiments (b).

Scanning and Growth Measurement.
After six weeks of growth, the samples were carefully removed, and the roots were separated from the soil using the wet hand-washing method described by Schuurman et al. (1965). The growth rate was then assessed by measuring the total length and average diameter of the grassroots, using the WinRHIZO root-scanning software (Regent Instruments Inc., Ottawa, ON, Canada) as described by Pang et al. (2011). To ensure consistent results, each root sample was scanned five times with different orientations of the roots.

Direct Shear Tests.
For the direct shear tests, samples similar to those used in the wet hand-washing process were extracted. Direct shear rings were embedded into the soil within the containers to extract the samples. A spoon was placed at the bottom of the containers to support the soil and minimize disruption. Samples were extracted and the top 15 mm was removed to expose the root area, and trimmed from the bottom to obtain the final height of 28.5 mm. The above-ground parts of the plants were pruned, and the samples were carefully removed from the rings.

The shear tests were performed following ASTM D3080 standards using a custom-designed shear box. Because the tests focused on shallow soil depths, a high-precision shear box was created to accommodate very low to zero vertical stresses as shown in Figure 2. Data collection was conducted at a rate of one sample per second using an ADMET 600 Series Load Cell - 11 LBF (50N) with a resolution of 0.001. To reduce friction between the shear box's top and bottom platens, automotive grease was applied. Vertical pressures of 0.201, 0.268, and 0.335 kPa were applied to the samples using dead weights. These pressures were determined by calculating the effective stress at a depth of 15 mm, which is representative of surface soils. The shearing rate was set to 0.05 mm/min to ensure adequate drainage during the test. To account for the reduction in area during shearing, the area correction for circular direct shear was applied (Bareither et al., 2008). The results of shear stress versus horizontal deformation for the considered three normal stresses were averaged, as differences among the results were minimal due to the low-stress levels.

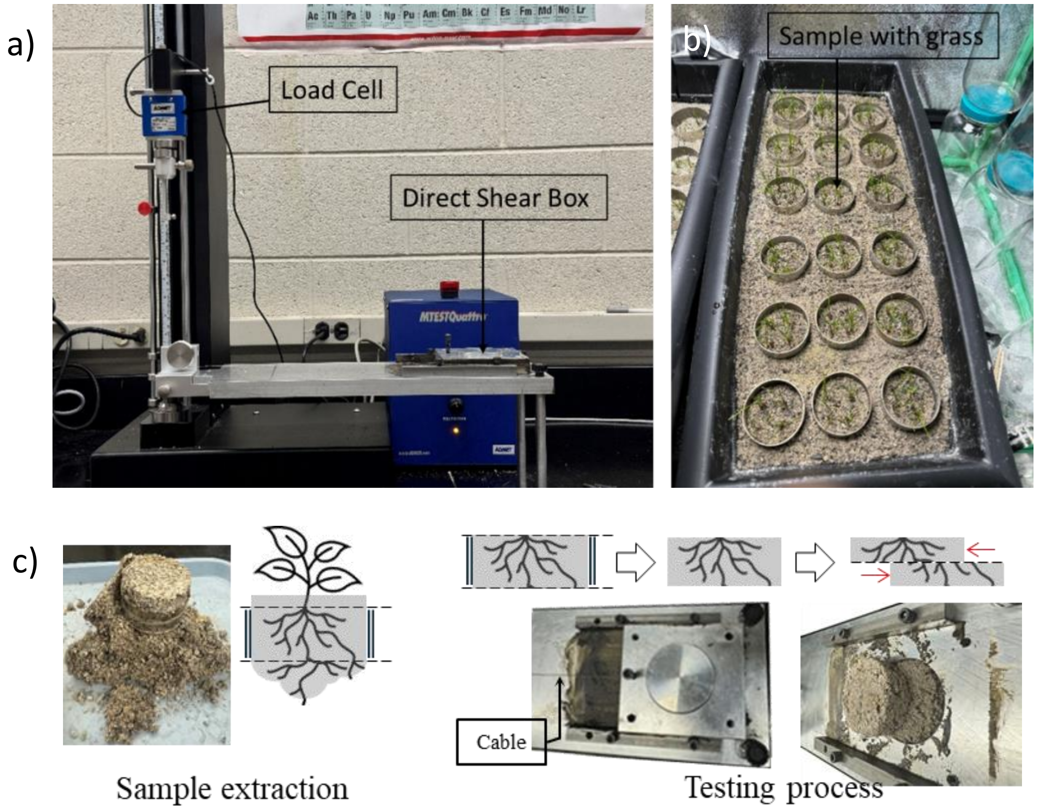
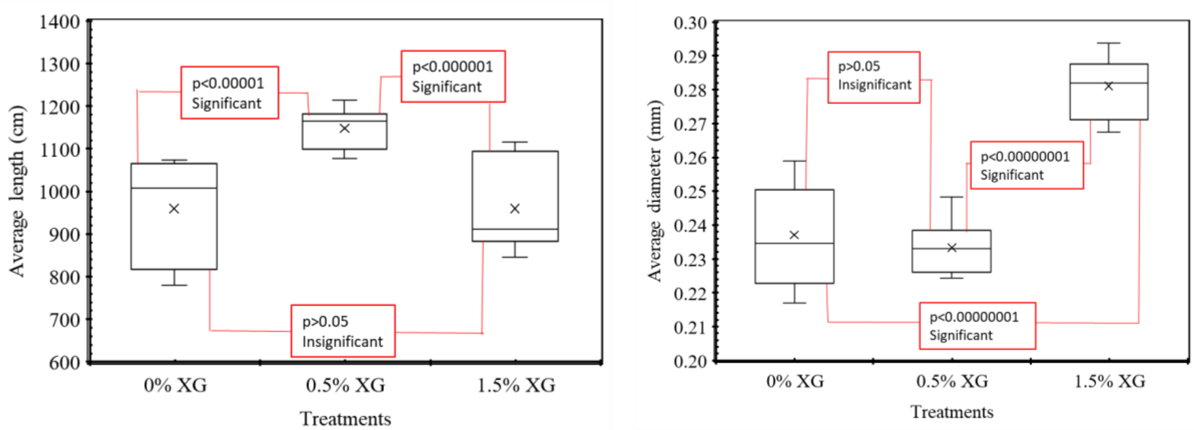


Figure 2: (a) Customized Direct Shear Apparatus, (b) Cultivation Box, and (c) sketch of the testing procedure.

RESULTS AND DISCUSSION

Root Growth Study.

Figure 3(a) presents the average root length growth across different treatment samples, with the y-axis indicating the total root length as measured by the WinRhizo software. To maintain consistency, each box and whisker plot includes data from three samples, each of which was scanned five times with different ordinations. The 0% XG samples exhibited a median root length of 1012 mm, which was longer than the 906 mm observed in the 1.5% XG samples, but shorter than the 1174 mm recorded in the 0.5% XG samples. After 6 weeks, the low XG concentration appears to increase root length, whereas the high XG concentration limited root elongation. The difference in root length between 0.5% XG and the other two cases is significantly different, which implies the difference is due to the effect of the treatment. However, length data of 0% XG and 1.5% XG are not statistically significant, which suggests more sample needs to be tested to understand the difference in length growth.



(a) (b)

Figure 3: The average total length for different treatment types at 6 weeks age (a), The average diameter for different treatment types at 6 weeks age (b).

Figure 3 (b) illustrates the average root diameter across different sample treatments. The 0% XG samples exhibit an average root diameter of approximately 0.24 mm, with greater variability compared to the treated samples. In the 0.5% XG-treated samples, the average root diameter decreases slightly to 0.23 mm, with reduced variability. Conversely, the 1.5% XG-treated samples display an increased average root diameter of 0.28 mm. These findings suggest that after 6 weeks, lower concentrations of XG biopolymer promote the growth of longer, thinner roots, while higher concentrations result in shorter, thicker roots. This indicates that XG biopolymer influences root development by slightly reducing root diameter at lower concentrations while promoting elongation, and by enhancing root diameter growth while inhibiting elongation at higher concentrations. The difference in root diameter between 1.5% XG and the other two cases is significantly different however, root data of 0% XG and 0.5% XG are not statistically significant. The *p*-values are reported in Figure 3.

Shear Strength.

Figure 4 shows the shear stress versus horizontal deformation plots for freshly prepared 0% XG samples and those treated with xanthan gum (XG). The average water content of the 0% XG samples was 7.5%, while the XG-treated samples had an average water content of 6.5% after testing. The XG-treated specimens exhibit a similar initial shear stress slope with horizontal deformation when compared to the 0% XG samples, with all specimens demonstrating strain hardening behavior and slight variations in maximum shear stress. The comparable initial stiffness suggests that fresh xanthan gum does not significantly impact small deformations. However, xanthan gum does appear to influence the maximum shear stress, with the 1.5% XG-treated samples showing a 29% increase in maximum shear stress, and the 0.5% XG-treated samples exhibiting a similar response, though with a marginal reduction in maximum shear stress.

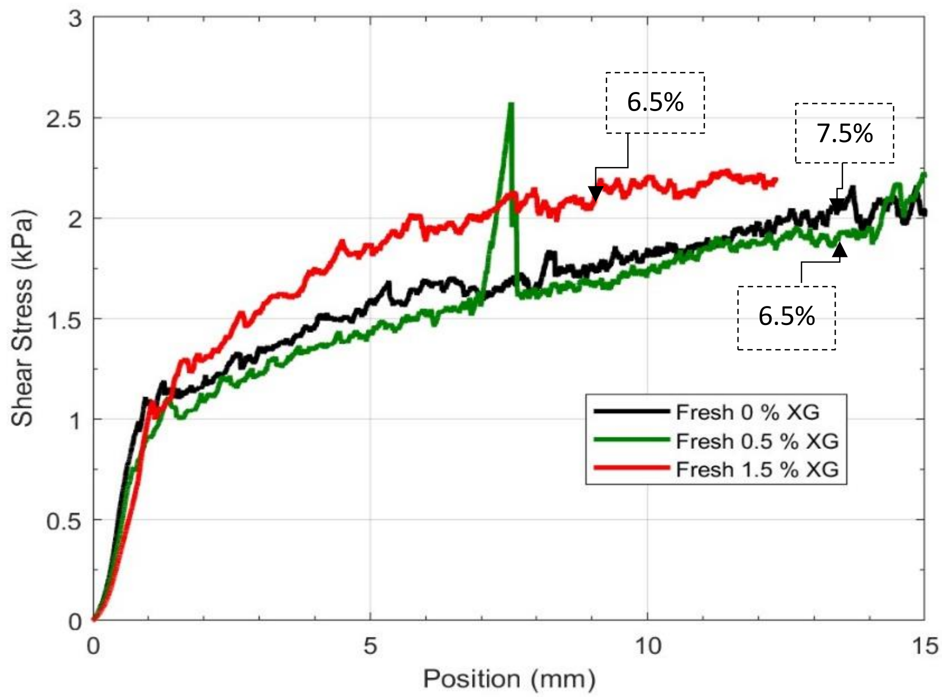


Figure 4. Shear Stress vs Horizontal Deformation for Fresh prepared 0% XG sample, 0.5% XG treated sample, and 1.5% XG treated sample (the labels on the graph show the water content of the specimen).

Figure 5 presents the shear stress versus horizontal deformation plots for 0% XG samples and xanthan gum (XG)-treated samples with 6-week-aged roots. The 0% XG samples with 6-week roots exhibited a maximum shear stress of 2.8 kPa. In comparison, the 0.5% XG-treated sample with roots demonstrated a significant increase in maximum shear stress, reaching 4.5 kPa, which represents a 61% increase compared to the 0% XG sample. The 1.5% XG-treated sample exhibited an even greater enhancement, with a 105% increase in maximum shear stress, achieving a peak value of 5.75 kPa. It is important to note that the water content varied among the samples, with the 0% XG sample, 0.5% XG-treated sample, and 1.5% XG-treated sample having water contents of 2%, 8.3%, and 5.4%, respectively. This variation in water content, despite the samples being prepared and cured in an identical manner, contributed to differences in the shear stress versus horizontal deformation curves. The variation in the water content is due to variation in the humidity of the lab environment as well as due to sampling at different times after watering.

Interestingly, the 0% XG sample with roots and the 0.5% XG-treated sample with roots exhibited strain-hardening, while the 1.5% XG-treated sample with roots displayed strain-softening. These observations suggest that higher concentrations of biopolymer, in conjunction with root presence, not only enhance the shear strength of the soil but also shift its behavior from strain-hardening to strain-softening.

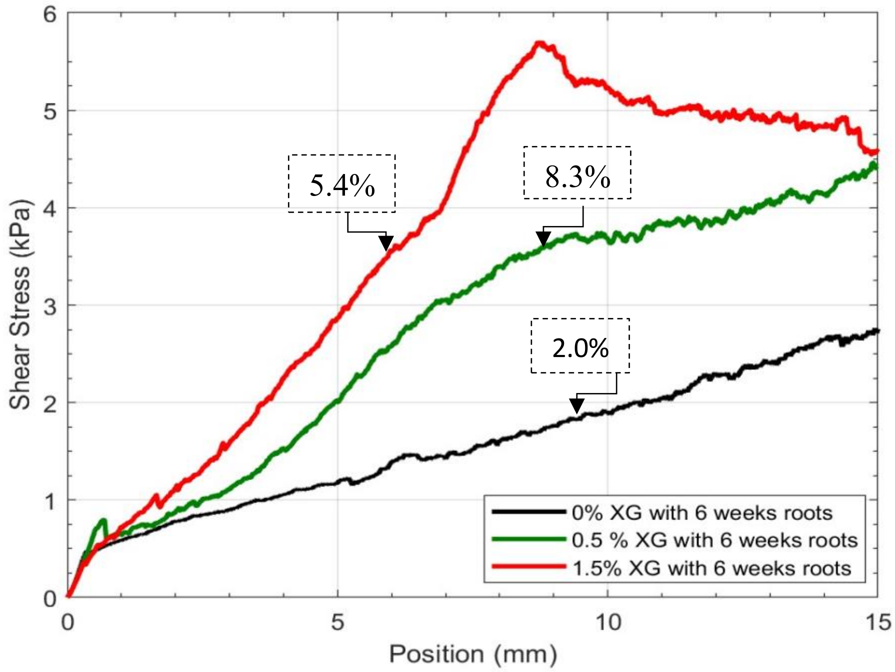


Figure 5: Shear Stress vs Horizontal Deformation for 0% XG sample, 0.5% XG treated sample, and 1.5% XG treated sample with 6-week aged roots (the labels on the graph show the water content of the specimen.

CONCLUSION

This study explored the enhancement of shear strength of course-grained soil (Acco sand) through the application of xanthan gum (XG) biopolymer. The investigation compared the shear strength of freshly treated sand to untreated sand (0% XG) and the shear strength of sand with 6-week-aged roots to XG-treated sand with similarly aged roots. Results indicated that while biopolymer treatment in fresh samples did not significantly enhance shear strength at lower deformations, it did positively impact shear strength at higher deformations, particularly with increased biopolymer concentrations. With roots, sand treated with 0.5% XG and 1.5% XG at 6 weeks of age exhibited a significant increase in shear strength, of 29% and 105% higher than untreated sand with aged roots. This highlights the more pronounced strength enhancement achieved through the combined effect of biopolymer and root growth.

Furthermore, at higher XG concentrations, the soil's behavior shifted from strain hardening to strain softening, suggesting a change in mechanical properties. This could be due to the formation of stiffer bonds between particles at higher XG concentrations and lower water contents. However, a more in-depth study of the underlying mechanism for this shift is underway.

Variations in water content across the samples, despite identical preparation methods, indicate that moisture plays a crucial role in the interaction between XG and soil-root systems, a finding that will be studied in more detail in our future tests. These findings emphasize the potential of XG as an effective biopolymer for long-term soil stability and shear strength enhancement, with significant implications for erosion control and slope stabilization. However, the transition to strain-softening at higher XG concentrations underscores the need for careful consideration of biopolymer dosage in practical applications.

ACKNOWLEDGMENT

This material is based upon work supported by the U.S. Army Corps of Engineers under contracts W912HZ-20-2-0054, W912HZ-21-2-0034, and W912HZ-21-C-0056. The discussions and conclusions presented in this work reflect the opinions of the authors only.

REFERENCES

Bareither, C. A., Benson, C. H., and Edil, T. B. (2008). "Reproducibility of direct shear tests conducted on granular backfill materials." *Geotechnical Testing Journal*, 31(1), 84-94.

Chang, I., Jeon, M., and Cho, G.-C. (2015). "Application of microbial biopolymers as an alternative construction binder for earth buildings in underdeveloped countries." *International Journal of Polymer Science*, 2015, 1-9.

Chang, I., Lee, M., Tran, A. T. P., Lee, S., Kwon, Y. M., Im, J., and Cho, G. C. (2020). "Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices." *Transportation Geotechnics*, 24, 100385.

Chen, C., Zesen, P., JiaYu, G., Yaxiong, P., Xiaoyang, H., and Li, W. (2020). "Exploring Environmentally Friendly Biopolymer Material Effect on Soil Tensile and Compressive Behavior*." International Journal of Environmental Research and Public Health* 17 (23), 9032. https://doi.org/10.3390/ijerph17239032 .

Ekanayake, J. C., Marden, M., Watson, A. J., and Rowan, D. (1997). "Tree roots and slope stability: a comparison between Pinus radiata and kanuka." New Zealand *Journal of Forestry Science*, 27(2), 216-233.

Fatehi, H., Ong, D. E., Yu, J., and Chang, I. (2021). "Biopolymers as green binders for soil improvement in geotechnical applications: A review." *Geosciences*, 11(7), 291.

Garcıa-Ochoa, F., Santos, V. E., Casas, J. A., & Gómez, E. (2000). "Xanthan gum: production, recovery, and properties." *Biotechnology Advances*, 18(7), 549-579.

Ghestem, M., Guillaume, V., Alain, B, Quentin, V., and Alexia, S. (2014). "Influence of Plant Root System Morphology and Architectural Traits on Soil Shear Resistance." *Plant and Soil* 377, 43–61. https://doi.org/10.1007/s11104-012-1572-1

Hiraishi, T., and Taguchi, S. (2009). "Enzyme-catalyzed synthesis and degradation of biopolymers." *Mini-Reviews in Organic Chemistry*, 6(1), 44-54.

Ladd, R. S. (1978). "Preparing test specimens using undercompaction." *Geotechnical Testing Journal*, 1(1), 16-23.

Li, P., and Li, Z. (2011). "Soil reinforcement by a root system and its effects on sediment yield in response to concentrated flow in the loess plateau." *Agricultural Sciences*, 2(2), 86.

Pang, W., Crow, W. T., Luc, J. E., McSorley, R., Giblin-Davis, R. M., Kenworthy, K. E., and Kruse, J. K. (2011). "Comparison of water displacement and WinRHIZO software for plant root parameter assessment." *Plant Disease*, 95(10), 1308-1310.

Reubens, B., Jean, P., Frédéric, D, Guy, G., and Bart, M. (2007). "The Role of Fine and Coarse Roots in Shallow Slope Stability and Soil Erosion Control with a Focus on Root System Architecture: A Review." *Trees* 21 (4), 385–402. https://doi.org/10.1007/s00468-007-0132-4 .

Schachtman, D. P., Robert, J.R., and S.M. Ayling. (1998). "Phosphorus Uptake by Plants: From Soil to Cell." *Plant Physiology* 116 (2), 447–53. https://doi.org/10.1104/pp.116.2.447 .

Schuurman, J. J., and Goedewaagen, M. A. (1965). "Methods for the Examination of Root Systems and Roots." *Soil Science Society of America Journal*.

Tengbeh, G. T. (1993). "The effect of grass roots on shear strength variations with moisture content." *Soil Technology*, 6(3), 287-295.

Wang, S., Zhao, X., Zhang, J., Jiang, T., Wang, S., Zhao, J., & Meng, Z. (2023). "Water retention characteristics and vegetation growth of biopolymer-treated silt soils." *Soil and Tillage Research*, 225, 105544.

Zhou, Z. C., and Shangguan, Z. P. (2007). "The effects of ryegrass roots and shoots on loess erosion under simulated rainfall." *Catena*, 70(3), 350-355.