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Non-Structural Slope Stabilization Using Biopolymers

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Abstract

Non-structural slope stabilization techniques are gaining popularity for cost-affordability and environmental sustainability and are intended primarily to enhance the soil shear strength parameters. The present study evaluates the performance of three biopolymers: Guar Gum, Gellan Gum, and Xanthan Gum as slope stabilizers for a quintessential soil slope of a local district in the foothills of the Lesser Himalayas. The study measures the shear strength of biopolymer-treated soil at varying concentrations and moisture contents, and concludes that the soil shear strength is highly influenced by the concentration of biopolymer and the moisture content. The results demonstrate significant increase (48% and 7%) of the cohesion and friction angle of a particular biopolymer-treated sample for a specific moisture content. However, the addition of biopolymers to the soil also leads to a decrease in the permeability of the original sample. The study, in the next phase, numerically computes the Factor of Safety of the test-bed slope before and after the application of biopolymers, and observes that the addition of biopolymers in soil significantly increases (34%) the factor of safety at an optimum combination concentration and moisture content for all three biopolymers. This signifies their utility as non-structural slope stabilizers. By highlighting the improved shear strength of the biopolymer-treated soils, the study complements the current initiatives for non-structural slope stabilization and sustainable soil enhancement and adds to the new yet expanding body of information regarding long-term, non-structural slope stabilizing techniques.

1. Introduction

The persistent slope failures in the Himalayan region are attributed to its complex and brittle geology, juxtaposition of heterogenous slope materials (especially at plate boundaries), high relative relief, and active tectonism, along with high volume of precipitation [1,2]. With the construction of various roads and other large structures into these fragile mountain belts, the problems of slope failures have become execrated and require immediate intervention [2,3]. Kumari et al. [4] observed significant climate change projections on landslide hazards, emphasizing the increased occurrence of landslides attributed to shifts in precipitation patterns and heightened pre-monsoon rainfall. The slope failures in the Shimla Hills region, another high exposure centre in the Himalayan region, are caused by multiple factors such as permafrost, deforestation, heavy rainfall, toe-cutting of valley side slopes, erosion, geological instability, and stone quarrying [5]. For the entire Himachal Pradesh, especially where road widening projects are ongoing, pre-disaster slope stability analysis becomes essential for risk management for landslide hazard mitigation as it offers valuable insights to planners and engineers [6]. Singh et al. [7] observed the complexity of landslide problems in the Himalayan hilly terrains, often compounded by developmental activities, and highlighted the importance of predictive indications in mitigating the slope failures effectively. Dahal et al. [8] examined spatial variations in landslide occurrences based on soil properties and internal friction angles and reported that clay minerology and transient pore water

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pressure played a significant role in triggering landslides in the Himalayas. Nath et al. [2, 3] suggested a strong corelation between Himalayan seismicity and the slope failures. All these studies recommend immediate establishment of a framework for landslide risk mitigation in the Himalayan region considering the direct and indirect socio-economic implications of recurring slope failures in the Himalayas. Conventional slope stabilization methods often apply structural measures, but there have been concerns over the environmental impact and cost-effectiveness of such structural measures in the scientific community. Also, there is ample evidences of failure of structural slope stabilizers (primarily retaining walls) in the Himalayan region, as depicted in Figure 1. The primary causes of such failures include (but are not limited to) quality of construction, unfavourable slope morphometry and a very high volume of precipitation.

Figure 1 Poor performance of retaining walls in the Himalayan region, especially where road construction is ongoing

In this context, the application of biopolymers as a potential non-structural slope stabilizer has emerged as a viable alternative owing to their cost effectiveness and environmental sustainability. The main advantage of biopolymers is attributed to their hydrocolloid rheology, which enables them to efficiently coagulate mixtures to keep constituents from separating [9]. Fatehi et al. [10] observed that when biopolymer was added to sandy soil, the dissolved particles began to migrate within the holes and permeate the sand's surface. The biopolymer particles formed a very strong film adhering to the sand particles. This initiated a bridging sequence to start the bonding process: making the geotechnical performance better. For silty sandy soils, the addition of biopolymers enhanced both shear and compressive strengths [11] and similar observations were true for soft clay as well [12]. Chang et al. [13,14] examined the effectiveness of Xanthan Gum in strengthening diverse soil types, offering an eco-friendly alternative to conventional materials. Similarly, Chang et al. [14] reported the versatility of Gellan Gum as a soil improvement material for practical construction applications. Caballero et al. [15] demonstrated the promising capacity of Guar Gum to enhance soil stability, aligning with the broader exploration of biopolymers. Orts et al. [16] showcased the versatility of biopolymers with their exploration of polyacrylamide (PAM), emphasizing its role in erosion control and runoff reduction across industries. Etemadi et al. [17] discussed the environmental aspects by investigating biopolymers' potential in immobilizing hazardous metallic wastes in the subsoil, widening the scope of biopolymer applications. Many other researchers have demonstrated enhanced geotechnical properties of biopolymer-treated soils [15-18]. Fatehi et al. [18] suggested the diverse applications of biopolymers, extending beyond Xanthan Gum and Gellan Gum [19]. Other studies collectively affirmed the potential of biopolymers in enhancing soil properties and stabilizing slopes, offering a wide array of alternatives suited to varying geological conditions [20-24]. These studies undoubtedly present a compelling case of the utility of biopolymers as a non-structural stabilizer with promising outcomes, although certain aspects remain to be thoroughly explored. The long-term impacts of biopolymer-reinforced soil, accounting for soil erosion and vegetation growth, require further in-depth investigations. Additionally, understanding the resilience of biopolymer-treated soil under diverse environmental conditions, including freeze-thaw cycles, represents a frontier for future research.

An endeavour has been made in the present study to assess the efficacy of three biopolymers in improving soil stability in a part of Himachal

Pradesh, India, located at an elevation of 900 meters above mean sea level. Owing to the inherent soil types and climate conditions, the slopes of this region are susceptible to failure and often require mitigatory measures. To comprehend the local geotechnical context, an initial assessment is necessary for the engineering parameters, which include soil classification and measurement of soil unit weight, internal friction angle, and cohesiveness. In compliance with the relevant Indian Standard Code of Practice, the prescribed laboratory tests were conducted. The main objective of the study is to determine the optimum combination of volume concentration of biopolymers and moisture content on a quintessential slope of the study area. The study aims to assess the performance the biopolymer-treated soil under varied volume concentrations of biopolymers and moisture contents and quantify the shear strength of biopolymer-treated soil samples using direct shear testing. As a direct application of these results, the study performs numerical analysis to determine the stability of the slope with a commercially available package (Geo 5) of the same slope before and after the introduction of biopolymers.

2. Problem Definition and Methodology

2.1. Soil properties

This study aims to investigate the effects of different biopolymers on the mechanical characteristics of cohesionless soil. The collected soil samples were divided into three primary groups: silt, sand, and gravel, depending on the size of their particles. In compliance with the relevant Indian Standard Codes of Practice, laboratory tests were conducted to determine the properties of soil. Table 1 enlists the physical attributes of soil specimens, which serves as the basis of the study. Furthermore, the grain size distribution curve of the collected specimen is shown in Figure 2. From the grain size distribution curve (Figure 2) and Table 1, the soil has been classified as SP-SM according to the unified classification. The authors did not perform Atterberg tests after adding the stabilizers because the focus of the study was primarily on evaluating the changes in shear strength and slope stability due to biopolymer addition. While Atterberg limits provide valuable information about soil plasticity and consistency, the main objective was to assess the direct impact of biopolymers on the mechanical behavior and stability of the soil. Therefore, resources and efforts were directed towards conducting shear tests and slope stability analyses, which were more pertinent to the study's goals of understanding and improving soil strength and stability through biopolymer treatment.

Table 1. Physical Characteristics of the Soil Samples

Parameters	Values
Gravel (%)	19.80
Sand (%)	76.40
Silt (%)	3.78
Bulk Unit Weight (gm/cm^3)	1.926
Dry Unit Weight (gm/cm^3)	1.650
Water Content	16.67
Fineness Modulus	6.25
Relative Density (%)	82.96
Permeability (cm/sec)	$3.162 * 10^{-3}$
Coefficient of Uniformity	9.86
Coefficient of Curvature	0.748
Cohesion (kg/cm^2)	0.03849
Angle of Internal Friction (°)	37.328
Elasticity Modulus, E (MPa)	70
Poisson's Ratio, ν	0.3
Soil Type	SP-SM

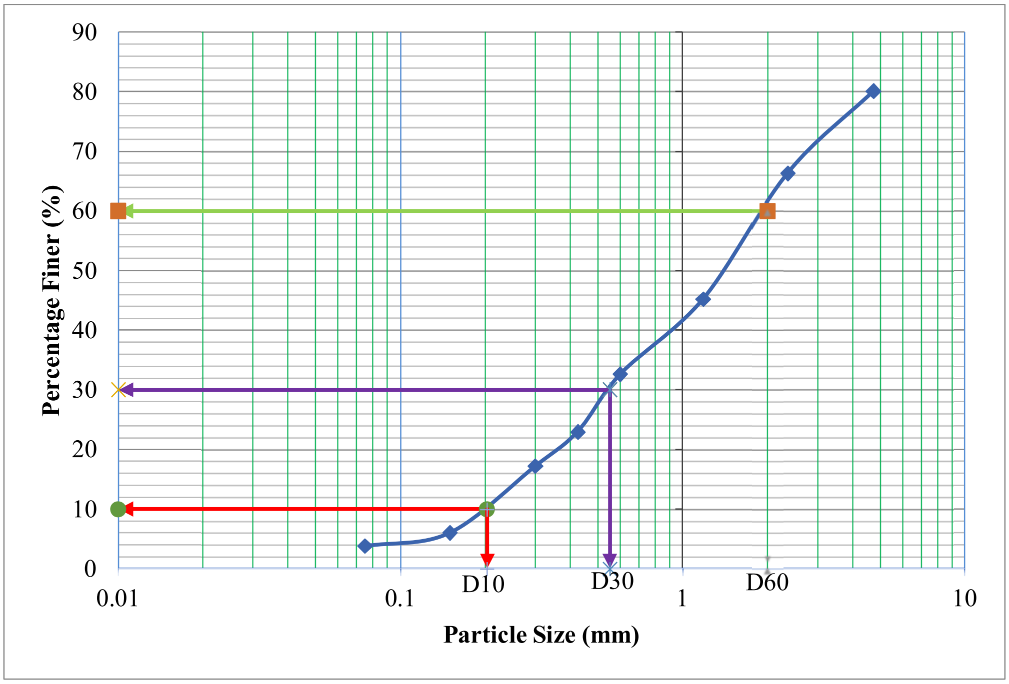

Figure 2 Grain size distribution curves for the soil used in this study

2.2. Properties of Biopolymers

The selection of biopolymers in this study was based on their cost-effectiveness and distinctive functional characteristics compared to other biopolymers. Xanthan gum, an anionic polysaccharide, is derived from the aerobicc fermentation of sugar by the bacterium Xanthomonas campestris. Its linear 1,4-linked β-D-glucose backbone, with every two units connected to a charged trisaccharide side chain, is well-documented in studies [25]. Guar gum, another polysaccharide, comprises a linear chain of β 1,4-linked mannose units with galactose residues 1,6-linked at every other mannose, providing it with notable solubility and stabilizing potential. Literature, such as the work of [19], emphasizes the effectiveness of guar gum in soil stabilization due to its numerous galactose branch points. Gellan gum, recognized for its remarkable gelling and stabilizing properties, is a microbial polysaccharide produced through bacterial fermentation. The microbial origin and gelling properties of gellan gum have been extensively explored in previous studies [26]. Its suitability for various applications, including the food and pharmaceutical industries, is attributed to its ability to form gels at low concentrations.

To find out how the biopolymers (Guar Gum, Gellan Gum and Xanthan Gum) can improve the shear strength characteristics of sandy soil slopes, the slope material's index and shear strength values were determined by laboratory testing. Details regarding the physical attributes of soil specimens are listed in Table 1. For soil stability, varying quantities of the Guar Gum, Gellan Gum and Xanthan Gum biopolymers (0.2%, 0.4%, and 0.5%) were used in this study. Biopolymers improve soil stability through several mechanisms. Firstly, biopolymers promote clay platelet aggregation, enhancing the soil's permeation behavior and reducing its permeability. This aggregation strengthens the soil structure, making it more resistant to cracks and erosion. Additionally, biopolymers bind soil particles together, increasing cohesion and reducing the risk of particle disintegration. Moreover, they can modify the soil's pore-network morphology, improving its mechanical properties such as compressive strength and shear resistance. Overall, biopolymers interact with soil minerals to enhance soil stability while offering environmental benefits compared to traditional stabilizers like cement or lime. The authors would like to emphasise that the field of biopolymer-treated soil stabilization is still developing, and more comprehensive studies are required to fully understand their behaviour.

2.3. Specimen Preparation

The soil samples were oven dried, at 104°C for 24 hours as per the relevant Indian Code of Practice. Next, a biopolymer powder is mixed with deionized water at various concentrations to form gels, which would act as colloids to thicken water-based systems. The concentration was computed by dividing the weight of the powder by the weight of the entire solution. To preserve the homogeneity of the solution and avoid clumping, the powder was carefully mixed into the water, stirring until a smooth consistency was reached. Figure 3 shows the sample preparation of Gaur Gum, Gellan Gum and Xanthan Gum, respectively. In the current study, Indian Standard IS 2720 (Part 13): 1986, "Direct Shear Test Methods of Soil Testing" was used for determining the strength parameters of soil and soil mixed with biopolymers. This standard provides thorough guidelines for assembling testing apparatus, getting specimens ready, and analyzing results. Since pore water pressures are released during direct shear testing, they are drained, which is why u = 0. Consequently, c' = c and φ' = φ.

Peak shear stresses are recorded with each applied normal stress in a direct shear test. For each of the "n" examined samples, there will be "n" normal and peak shear stresses. For a given soil, the shear strength parameters "φ" and "c" can be obtained by plotting the peak shear stress against the normal stress. Soil samples mixed with Gaur Gum, Gellan Gum, Xanthan Gum biopolymers for the direct shear test are depicted in Figures 4a, b and c, respectively. Biopolymer concentrations of 0.2%, 0.4%, and 0.5% by weight were the main focus of the investigation. The soil and solution were carefully combined at these concentrations until a homogenous mixture was achieved. The water content of the original soil sample was 16.67%, and the 14% water content has also been taken to find the effect of moisture content in the test results. This approach allowed for a comparative analysis of the soil's behavior under different moisture conditions, enhancing the understanding of how biopolymer stabilization affects soil stability across varying water content levels. Therefore, test samples with water levels of 14% and 16.67% were created.

(a) (b) (c)

Figure 3 Samples preparation (a) Gaur Gum (b) Gellan Gum (c) Xanthan Gum

(a) (b) (c)

Figure 4 Soil samples for Direct shear test (a) Gaur Gum (b) Gellan Gum (c) Xanthan Gum

3. Results and Discussions

3.1. Stabilization with Gaur Gum

Figures 5 and 6 depict the comparison between different concentrations of GG biopolymer and the original soil at moisture contents of 16.67% and 14%, respectively. The enhancement in soil shear strength parameters for sandy soil treated with GG indicates a significant increase in strength of the sand. The responses of the samples to various maximum normal stresses (0.0138, 0.027, and 0.0416 kg/cm^2) during the experimentation were measured. The alteration in the soil behavior demonstrates GG's capacity to influence the resilience and efficiency of sandy soil.

Table 2 summarizes the shear strength parameters for different concentrations of Gaur Gum with original soil at different moisture contents. From Table 2, it can be noticed that maximum shear strength was obtained for GG concentrations of 0.4% at a moisture content of 16.67% and for GG concentrations of 0.5% at a moisture content of 14%. Therefore, it can be concluded that the shear strength of soil is highly influenced by the concentration of GG and moisture content. For finding the optimum concentration of GG biopolymer, laboratory tests should be performed at natural moisture content for different concentrations of GG biopolymer. Table 2 also suggests that the permeability of the original soil decreases after mixing with GG biopolymer. Due to this excess pore pressure might increase during an earthquake. Therefore, earthquake analysis is also needed to determine how much excess pore pressure will affect the soil's shear strength.

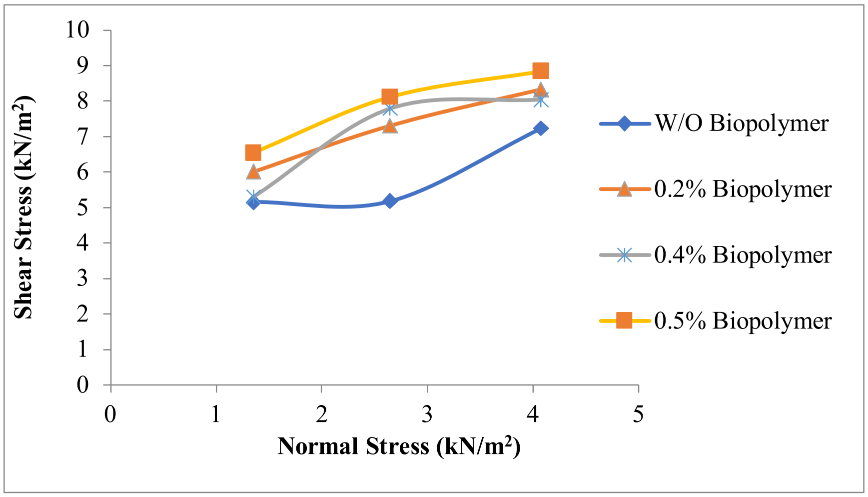

Figure 5 Comparison between various concentrations of GG biopolymer and the original soil at a moisture content of 16.67%.

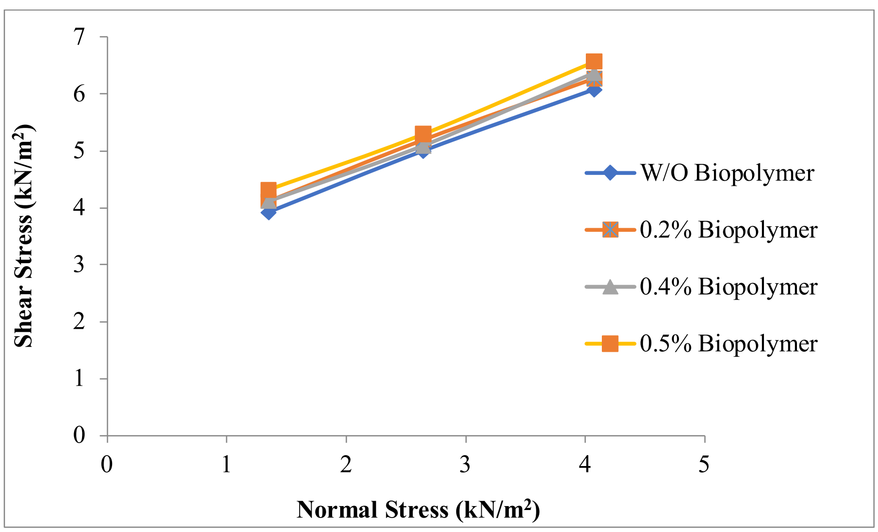

Figure 6 Comparison between different concentrations of the GG biopolymer and the original soil at a moisture content of 14%.

Table 2 Shear Strength parameters for different concentrations of Gaur Gum with original soil at different moisture content.

Concentration of biopolymers in the soil	At a moisture content of 16.67%.			At a moisture content of 14%		
	Cohesion (kN/m^2)	Friction Angle (deg.)	Permeability (cm/sec)	Cohesion (kN/m^2)	Friction Angle (deg.)	Permeability (cm/sec)
Without (W/O) Biopolymer	3.77	37.32	3.16×10^{-3}	2.872	38.31	2.95×10^{-3}
0.2%	4.93	40.32	7.91×10^{-4}	3.068	38.31	7.61×10^{-4}
0.4%	4.55	43.59	7.64×10^{-4}	2.97	39.60	7.01×10^{-4}
0.5%	5.58	40.08	7.89×10^{-4}	3.162	39.63	7.26×10^{-4}

3.2. Stabilization with Gellan Gum

Figures 7 and 8 show the comparison between different concentrations of Gellan Gum biopolymer and the original soil at moisture contents of 16.67% and 14%, respectively. The presence of Gellan Gum significantly increased the shear strength of the sand, as observed in the results. Various maximum normal stresses (0.0138, 0.027, and 0.0416 kg/cm^2) were applied to the samples, showcasing the influence of Gellan Gum on the resilience and overall usability of sandy soil.

Table 3 summarizes the shear strength parameters for various concentrations of Gellan Gum in the original soil at different moisture content levels. Table 3 indicates that the maximum shear strength was achieved with Gellan Gum concentrations of 0.5% at a moisture content of 16.67% and with Gellan Gum concentrations of 0.4% at a moisture content of 14%. This observation leads to the conclusion that the soil's shear strength is significantly influenced by the concentration of Gellan Gum and the moisture content. To identify the optimal concentration of Gellan Gum biopolymer, laboratory tests should be conducted at the natural moisture content for different concentrations of Gellan Gum. Additionally, Table 3 suggests a decrease in the permeability of the original soil after mixing with Gellan Gum biopolymer. This decrease in permeability raises concerns about excess pore pressure during seismic events. Therefore, a dynamic study is necessary to assess the impact of excess pore pressure on the soil's shear strength.

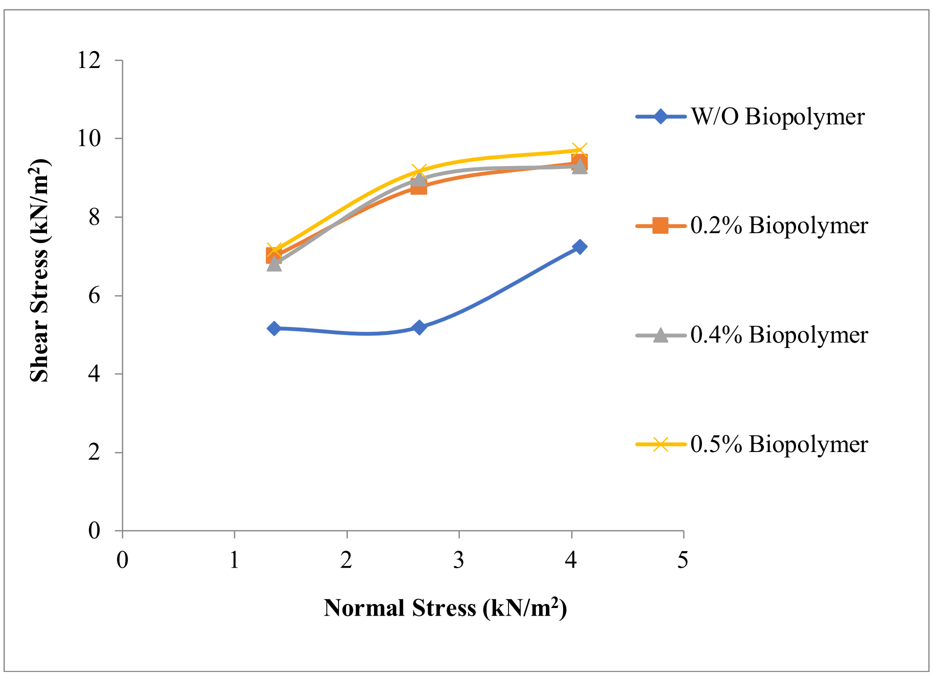

Figure 7 Comparison between various concentrations of Gellan Gum biopolymer and the original soil at a moisture content of 16.67%.

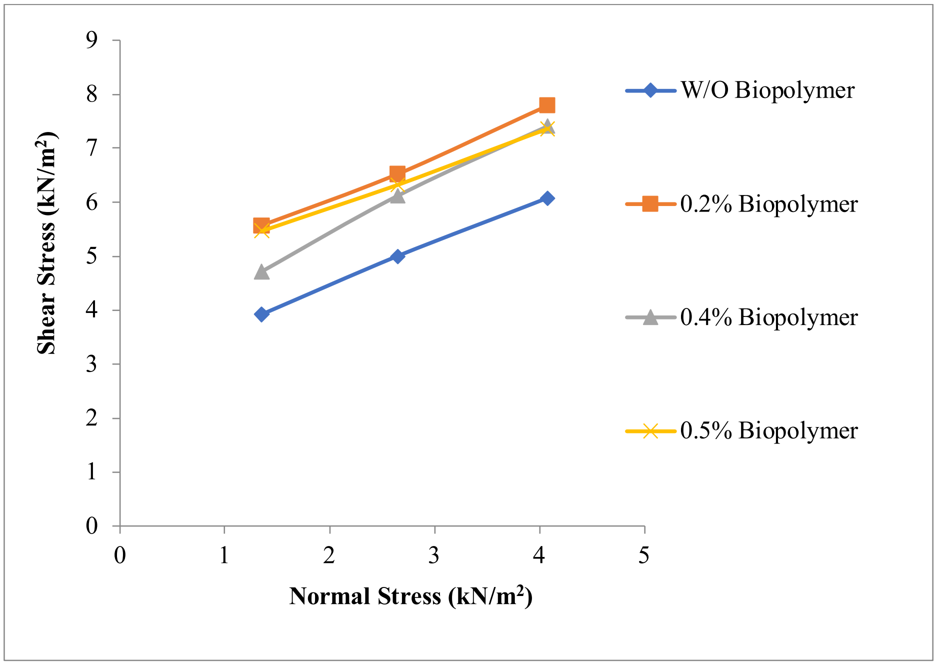

Figure 8 Comparison between different concentrations of Gellan Gum biopolymer and the original soil at a moisture content of 14%.

Table 3 Shear strength parameters for different concentrations of Gellan Gum with original soil at different moisture contents.

Concentration of biopolymer in the soil	At a moisture content of 16.67%.			At a moisture content of 14%		
	Cohesion (kN/m²)	Friction Angle (deg.)	Permeability (cm/sec)	Cohesion (kN/m²)	Friction Angle (deg.)	Permeability (cm/sec)
Without (W/O) Biopolymer	3.78	37.32	3.16×10^{-3}	2.87	38.31	2.95×10^{-3}
0.2%	6.06	41.15	7.01×10^{-4}	4.43	39.23	7.18×10^{-4}
0.4%	5.94	42.41	7.99×10^{-4}	3.42	44.68	7.91×10^{-4}
0.5%	6.18	43.19	7.22×10^{-4}	4.52	34.77	7.06×10^{-4}

3.3. Stabilization with Xanthan Gum

Figures 9 and 10 illustrate the comparison between various concentrations of Xanthan Gum biopolymer and the original soil at moisture contents of 16.67% and 14%, respectively. The addition of Xanthan Gum significantly enhanced the shear strength of the sand, as evident from the results. The maximum normal stresses applied to the samples were 0.0138, 0.027, and 0.0416 kg/cm². This change in behavior clearly illustrates the ability of Xanthan Gum to influence the practicality and durability of sandy soil.

Table 4 represents the shear strength parameters for various concentrations of Xanthan Gum in the original soil at different moisture content levels. The table indicates that the maximum shear strength was obtained with Xanthan Gum concentrations of 0.4% at both moisture contents of 16.67 and 14%. This observation leads to the conclusion that the soil's shear strength is highly influenced by the concentration of Xanthan Gum and the moisture content. To determine the optimum concentration of Xanthan Gum biopolymer, laboratory tests should be conducted at the natural moisture content for different concentrations of Xanthan Gum. Additionally, it can be noticed from Table 4 that there is a decrease in the permeability of the original soil after mixing with Xanthan Gum biopolymer. This decrease in permeability raises concerns about excess pore pressure during seismic events. Therefore, a seismic analysis is necessary to assess the impact of excess pore pressure on the soil's shear strength.

It is to be noted that as the field of biopolymer-treated soil is still in infancy, there is no Indian Standards developed yet formulating the guidelines on the concentration of biopolymer for a particular soil type. This is why the authors refer to the available literature on the same and assume that even with such low concentration of biopolymers, soil shear strength would increase significantly. This hypothesis is tested in the study and the results show positive outcome. The implication of such low requisite concentration of biopolymer is twofold: it provides economic/commercial viability and reduces the negative environmental impact. Considering the study as a prototype of its kind for the test bed selected, the authors are of the opinion that higher concentrations of biopolymers would increase the cost and environmental concerns without proportional benefits.

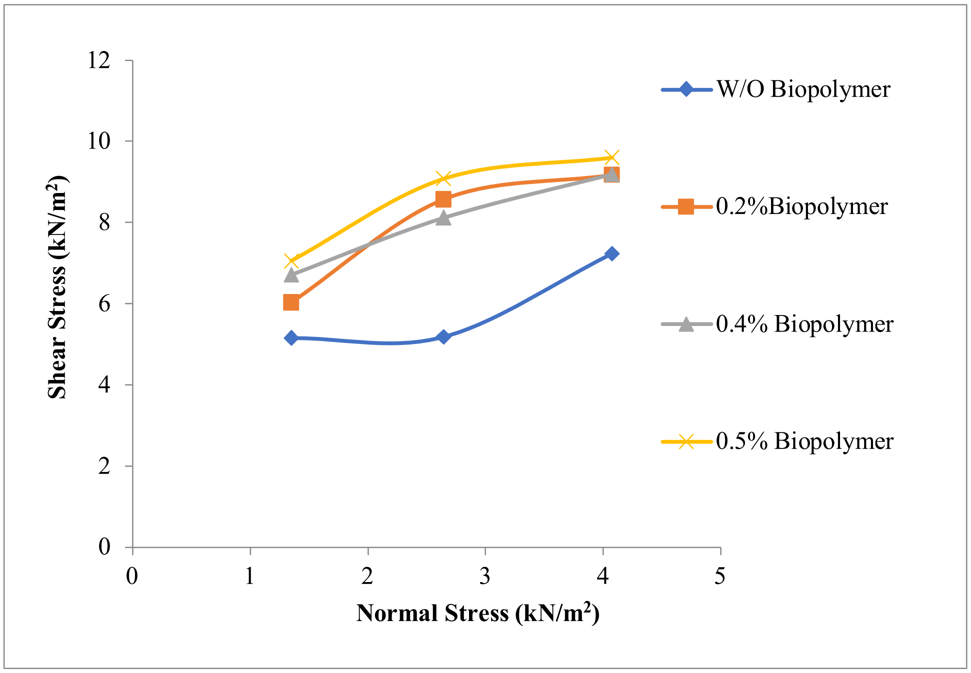

Figure 9 Illustrates a comparison between various concentrations of Xanthan Gum (XG) biopolymer and the original soil at a moisture content of 16.67%.

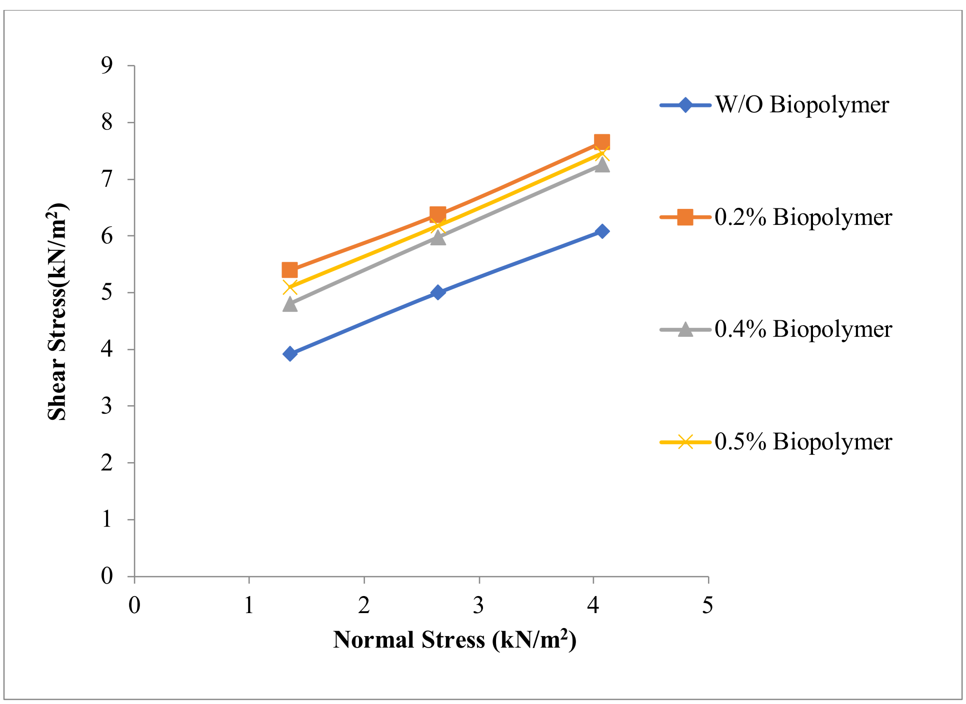

Figure 10 presents a comparison between different concentrations of Xanthan Gum (XG) biopolymer and the original soil at a moisture content of 14%.

Table 4 Shear strength parameters for different concentration of Xanthan Gum in the original soil at different moisture contents.

Concentration of biopolymer in the original soil	At a moisture content of 16.67%.			At a moisture content of 14%		
	Cohesion (kN/m^2)	Friction Angle (deg.)	Permeability (cm/sec)	Cohesion (kN/m^2)	Friction Angle (deg.)	Permeability (cm/sec)
Without (W/O) Biopolymer	3.77	37.32	3.16×10^{-3}	2.87	38.31	3.16×10^{-3}
0.2%	4.93	40.32	7.91×10^{-4}	4.24	39.60	7.91×10^{-4}
0.4%	4.56	43.59	7.64×10^{-4}	3.59	41.96	7.44×10^{-4}
0.5%	5.58	40.08	7.89×10^{-4}	3.92	40.80	7.01×10^{-4}

3.4. Slope Stability Analysis

The study uses commercially available Geo 5 slope stability software to calculate the safety factor (FoS). The input soil parameters were determined experimentally and are listed in Table 1. Geo 5 software used the universally accepted Mohr-Columb's failure criterion as the material constitutive model.

Geo 5 slope stability is a commercially available software which has been extensively used in both academia and industry. The application uses the concept of Limit Equilibrium to estimate the factor of safety of an input geometry under different loading conditions. As with the any stability software, the accuracy of the results provided by Geo 5 also depends on the input parameters viz. data quality (slope geometry, material property, groundwater condition and model constitutive laws) and the assumptions and simplifications made by the users. In this study, careful considerations were made to model the slope geometry and laboratory tests were performed to calibrate the material properties to accurately resemble the pertinent field conditions. While the authors acknowledge that use of other robust slope stability analysis techniques such as Finite Element Method may enhance the accuracy of the safety factor calculations further, we believe that within the scope and aim of the study (which is to test the performance of biopolymers as a non-structural slope stabilizers), application of limit equilibrium concept is justified.

The Bishop Method of Slices is used to assess the stability of slopes (particularly infinite slopes with assumed shallow circular failure mode) and determine the associated Factor of Safety (FoS) by solving three major equilibrium equations. It assumes that shear interslice forces acting at the lateral sides of each slice can be neglected. Like all other methods of slices, the Bishop method also relies on certain assumptions due to the inherent indeterminacy of the problem. However, the method exhibits satisfactory accuracy, with only slight deviations from the actual factor of safety (FoS) for slopes. Past study asserts that its precision is comparable to more intricate methods developed subsequently (such as the Spencer method), although researchers have not fully comprehended the underlying theoretical reasons for this phenomenon. According to past study the factor of safety (FoS) remains unaffected by the orientation of interslice forces, implying that the assumptions of the Bishop method have minimal impact on the results. Thus, the authors are of the opinion that the Bishop method provides reliable results with acceptable tolerance which makes it a widely used approach in geotechnical engineering.

In any numerical modelling of slope stability analysis, the robustness of the model is ensured through profiling accurate slope geometry and selecting appropriate material constitutive property. In this study, the input parameters for stability analyses are considered after much deliberation and careful considerations are made to ensure accurate slope profiling . Laboratory tests were performed to ensure selection of appropriate soil properties. The use of the Bishop method for computation of FoS is widely accepted. The study considers varying moisture contents to ensure the reliability of the results across diverse environmental conditions.

The methodology adopted in the study aligns with established principles, particularly referencing Geo 5 and the Bishop method, as highlighted in studies such as [23,25]. The development of the slope model, a pivotal component of this research, relies on extensive field surveys that yield precise measurements: a height of 4.45 meters, a width of 2.46 meters, and a slope inclination of 29 degrees. The field surveys for slope model measurements involved multiple check points and ground truthing. First, a clinometer, employing the direct stepping method was used to measure slope angles accurately. This method allowed for precise angle measurements by directly stepping along the slope while holding the clinometer level true. Subsequently, multiple measurements at various points along the slope were conducted to ensure comprehensive coverage. To validate the collected data, ground truthing was performed at different locations to minimize errors and ensure consistency. The soil properties such as cohesion (0.03849 kg/cm^2), bulk unit weight (1.926 gm/cm^3), and soil friction angle (37.328°) were used as input data to the software Geo5, as listed in Table 1. The values of the factor of safety calculated for various scenarios have been depicted in 11, 12 and 13 for different biopolymers. The values of FoS have also been summarized in Table 5. It can be observed that the addition of biopolymer to soil significantly increases the value of FoS. From Figures 11 – 13, it can be stated that the FoS values were found to be maximum for 0.4% Gaur Gum biopolymer mix, 0.5% Gellan Gum biopolymer mix and 0.4% Xanthan Gum biopolymer mix. Table 5 shows that the maximum and minimum values of FoS are observed for Gellan Gum and Xanthan Gum biopolymer mixes, respectively. The addition of different biopolymers indicate that both xanthan and guar gum achieve their maximum FoS at a 0.4% biopolymer-soil mix. Gellan gum reaches its peak FoS at a 0.5% biopolymer-soil mix. These trends suggest that the optimal concentration for enhancing slope stability varies with the type of biopolymer used. Xanthan and guar gum demonstrate significant improvements in soil stability at slightly lower concentrations, while gellan gum requires a higher concentration to achieve similar stability enhancements, as shown in Figures 11, 12, and 13.

The FoS (Factor of Safety) values in Table 5 were compared to standard safety thresholds, typically set at 1.3 to 1.5 for most slope stability applications. As per Indian Code of Practice (IS) 14458 (P-2): 1997, the recommended FoS of against sliding under static condition is 1.5. Other Indian Standards such as IS: 7894-1975 typically recommends a FoS of 1.5 under static conditions for any design considerations. The results of the present study show that xanthan and guar gum treated soil samples mixed at 0.4% and gellan gum at 0.5% concentration, achieved FoS values above this range, indicating effective stabilization. This practically implies that biopolymer-treated soils can meet or exceed safety requirements, offering an economical viable alternative to conventional stabilizers. However, it must be noted that prototype findings were environment-controlled in the laboratories, and further research is required to fully comprehend the performance of biopolymer-treated soil in the field conditions. Thus, large-scale application and effectiveness in diverse geotechnical settings require further validation.

The varying performance among biopolymers in FoS (Factor of Safety) results can be attributed to several factors. Each biopolymer interacts differently with soil particles due to variations in molecular structure and bonding mechanisms. Xanthan gum and guar gum, for instance, achieve maximum FoS at 0.4% concentration due to their optimal soil-binding properties at this ratio, enhancing shear strength and cohesion. Gellan gum performs best at 0.5%, possibly due to its unique gel-forming ability, which provides additional structural support. Soil type and moisture content also influence the effectiveness of each biopolymer, leading to differences in stabilization performance. The authors would like to emphasise that the field of biopolymer-treated soil stabilization is still developing, and more comprehensive studies are required to fully understand their behaviour.

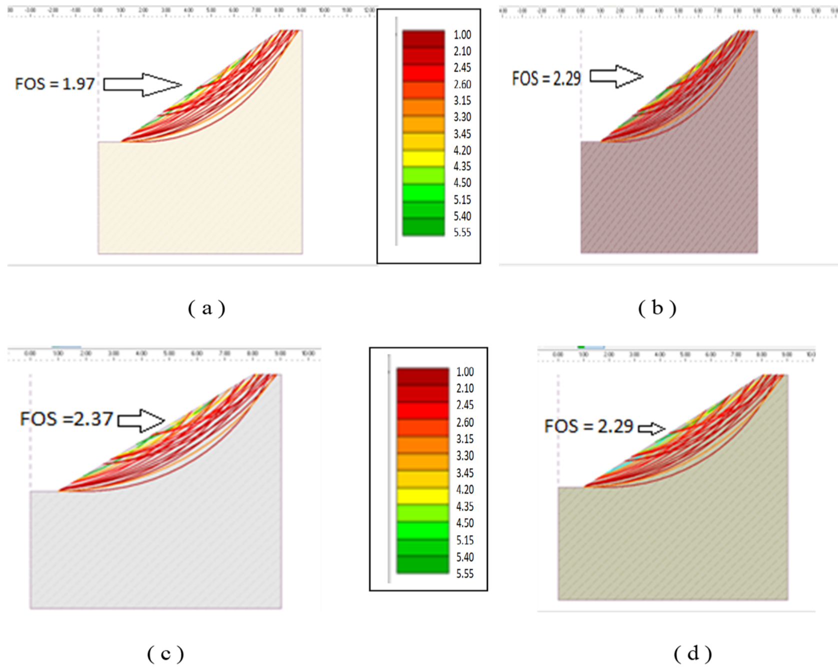

Figure 11 Slope stability for (a) the scenario without biopolymer, (b) with 0.2% Gaur Gum biopolymer, (c) with 0.4% Gaur Gum biopolymer, and (d) with 0.5% Gaur Gum biopolymer.

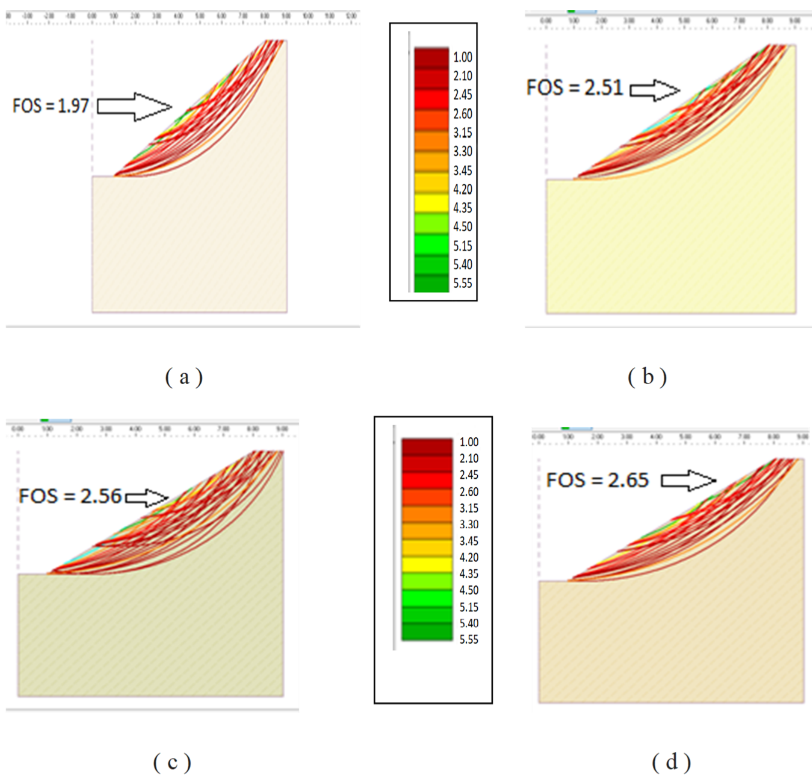

Figure 12 Slope stability for (a) the scenario without biopolymer, (b) with 0.2% Gellan Gum biopolymer, (c) with 0.4% Gellan Gum biopolymer, and (d) with 0.5% Gellan Gum biopolymer.

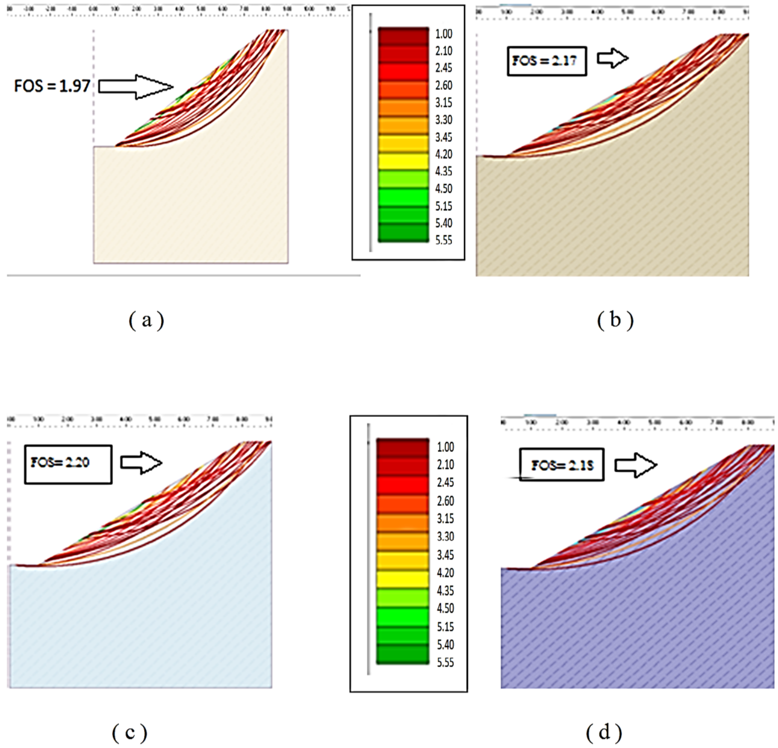

Figure 13 Slope stability for (a) the scenario without biopolymer, (b) with 0.2% Xanthan Gum biopolymer, (c) with 0.4% Xanthan Gum biopolymer, and (d) with 0.5% Xanthan Gum biopolymer.

Table 5 Factors of Safety for Various Scenarios

Soil Description	Case 1 Gaur Gum	Case 2 Gellan Gum	Case 3 Xanthan Gum
No stabilization	1.97	1.97	1.97
0.2% Biopolymer Soil mix.	2.29	2.51	2.17
0.4% Biopolymer Soil mix.	2.37	2.56	2.20
0.5% Biopolymer Soil mix.	2.29	2.65	2.18

4. Summary and Conclusions

The main aim of the study is to assess the performance of biopolymer-based additives on the improvement of the engineering properties of soil. The study uses a variety of laboratory experiments, which are permeability tests, density index assessments, and direct shear testing, to examine their impact on the soil shear strength, permeability, and environmental performance of the biopolymer-treated soil. The results of these studies show that biopolymer-based additions can lessen the environmental impact of soil while also increasing shear strength and decreasing permeability. Based on the study, the following conclusions can be drawn:

1. The shear strength of soil is highly influenced by the concentration of biopolymers and the moisture content.

2. Maximum shear strength was obtained with various concentrations of all three biopolymers and at different moisture contents. Therefore, laboratory tests should be conducted to find the optimum concentration of biopolymer used at the natural moisture content.

3. The addition of biopolymers to soil leads to a decrease in the permeability of the original soil. This might raise concerns about excess pore pressure during seismic events. Therefore, a dynamic study is necessary to assess the impact of excess pore pressure on the soil's shear strength.

4. The addition of biopolymers to the soil has significantly increased the value of the Factor of Safety (FoS) for a natural slope in the study area. The observed values of FoS were found to be maximum at 0.4% Gaur Gum biopolymer mix, 0.5 % of Gellan Gum biopolymer mix, and 0.4% Xanthan Gum biopolymer mix.

The study, however, also emphasizes the necessity of more research into the long-term impacts of biopolymer-reinforced soil, particularly soil erosion and vegetation growth. Furthermore, it is imperative to investigate the resilience of soil treated with biopolymers across a range of environmental circumstances.

The major limitations of biopolymer-treated soil are their environmental impacts: especially on soil permeability, and their availability and consistent quality. Many studies suggest that biopolymers often need extended curing times to achieve desired strength improvements. Long-term durability under diverse environmental conditions is still under investigation, and effectiveness can differ across soil types, necessitating tailored approaches. It is to be noted that prototype findings were environment-controlled in the laboratories, and further research is required to fully comprehend the performance of biopolymer-treated soil in the field conditions. Thus, large-scale application and effectiveness of biopolymer-treated soil in diverse geotechnical settings require further validation.

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تثبیت شیب غیر ساختاری با استفاده از پلیمرهای زیستی

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چکیده:

تکنیک‌های تثبیت شیب غیرسازه‌ای برای مقرون‌به‌صرفه بودن و پایداری محیط‌زیست محبوبیت پیدا می‌کنند و در درجه اول برای افزایش پارامترهای مقاومت برشی خاک در نظر گرفته شده‌اند. مطالعه حاضر عملکرد سه پلیمر زیستی را ارزیابی می‌کند: صمغ گوار، صمغ گلان، و صمغ زانتان به‌عنوان تثبیت‌کننده شیب برای یک شیب اصلی خاک یک منطقه محلی در دامنه‌های هیمالیا کوچک. این مطالعه استحکام برشی خاک تیمار شده با پلیمر زیستی را در غلظت‌ها و محتویات رطوبت مختلف اندازه‌گیری می‌کند و نتیجه می‌گیرد که مقاومت برشی خاک به شدت تحت‌تاثیر غلظت بیوپلیمر و محتوای رطوبت است. نتایج افزایش قابل توجهی (۴۸٪ و ۷٪) از پیوستگی و زاویه اصطکاک یک نمونه خاص تحت درمان با پلیمر زیستی را برای یک رطوبت خاص نشان می دهد. البته افزودن پلیمرهای زیستی به خاک نیز منجر به کاهش نفوذپذیری نمونه اصلی می شود. این مطالعه، در مرحله بعد، ضریب ایمنی شیب بستر آزمایش را قبل و بعد از کاربرد بیوپلیمرها به صورت عددی محاسبه می‌کند و مشاهده می‌کند که افزودن پلیمرهای زیستی در خاک به طور قابل توجهی (۳۴٪) ضریب ایمنی را در حد مطلوب افزایش می‌دهد. غلظت ترکیبی و محتوای رطوبت برای هر سه بیوپلیمر. این نشان دهنده کاربرد آنها به عنوان تثبیت کننده های شیب غیر ساختاری است. این مطالعه با برجسته کردن استحکام برشی بهبود یافته خاک‌های تیمار شده با پلیمرهای زیستی، ابتکارات فعلی را برای تثبیت شیب غیر ساختاری و تقویت پایدار خاک تکمیل می‌کند و به مجموعه اطلاعات جدید و در عین حال در حال گسترش در مورد تکنیک‌های تثبیت شیب بلندمدت و غیرساختاری اضافه می‌کند. .

کلمات کلیدی: پایداری شیب غیر سازه ای، مقاومت برشی خاک، پلیمرهای زیستی، پایداری شیب، FEM.