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Original Article

Utilizing Vetiver and Bamboo Fibers to Enhance Soil Stabilization in Arunachal Pradesh

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Abstract - *An innovative method of soil enhancement is biologically oriented in which chemical and biological processes are utilized for better soil improvements. The current research put forward a viable option through the improvement of sandy silt soil mechanical performance by vetiver and bamboo fibers along with Gaur Gum (GG) powder. In the experimental treatments, poorly-graded sandy soil was mixed with fibers, and GG powder and shear strength parameters were determined through direct shear tests. A falling head permeability test was performed for different reaction periods to measure the permeability of the soil. The results indicated that both vetiver and bamboo fibers cemented with GG significantly increased the shear strength of the sandy soil and reduced the permeability, with bamboo fiber demonstrating a greater improvement than vetiver. The introduction of these fibers facilitated additional interlocking, enhancing the cohesion among soil particles*.

Keywords *- Soil stabilization, Vetiver fiber, Bamboo fiber, Unconfined compressive strength, Permeability, Gaur Gum.*

1. Introduction

Soil stabilization techniques are crucial in civil engineering, particularly in areas with sandy soils prone to erosion and instability. Soil stabilization focuses on enhancing the engineering characteristics of the soil to boost its load-bearing capacity, reduce permeability, and control shrink-swell behavior (Lekha et al., 2015). This process encompasses a variety of techniques, broadly classified into three primary categories: mechanical, physical, and chemical methods. Fiber reinforcement in soil mechanics has recently attracted attention as a sustainable way to improve soil strength and stability. The incorporation of fibers not only enhances the strength of the soil but also promotes sustainability (Felisberto et al. 2017; Yu et al. 2017; Wang et al. 2017). In the past, various soil improvement techniques have been proposed and implemented to strengthen unstable areas prior to development. Soil stabilization methods can be categorized into two primary types: mechanical and chemical stabilization. Additionally, ashes from various organic materials resulting from combustion have been widely integrated into chemical stabilization processes (Celik & Nalbantoglu, 2013; Ozdemir, 2016).

However, the traditional stabilization methods, both mechanical and chemical, pose significant environmental challenges. Consequently, eco-friendly solutions are gaining preference in Geotechnical and Geo-environmental engineering as they emphasize long-term environmental sustainability. Engineers are now concentrating on using ground improvement techniques to transform weaker soils, ensuring sustainable land use. In recent times, in sustainable geotechnics, natural fiber materials are nowadays being used instead of synthetic materials to reinforce soils. This is because the behaviour of fibre-reinforced soil is determined through physical, mechanical and biological properties, which are fundamentally different from synthetic ones (Bordoloi et al. 2016). Different types of fibers are utilized to enhance mechanical properties. Geo-fibers have, in general, been applied for soil stabilization and improvement because they are inexpensive, lightweight, and definitely improve a considerable amount of strength. Geo-fibers improve sands' shear modulus, bearing capacity, and their resistance to liquefaction (John & Thomas, 2008). The selection of a reinforcing material should consider factors such as its cost-effectiveness, availability in supply, safety, and capability to enhance the mechanical properties of the soil. Natural fibers present several advantages, including affordability, biodegradability, and environmentally friendly characteristics.

However, fibres' effectiveness in soil reinforcement largely depends on their specific properties, such as composition, length, and fiber ratio. Currently, the enhancement of soil durability is being investigated through the incorporation of fibers. In 2009, Consoli et al. performed a range of conventional triaxial tests on sand samples enhanced with randomly dispersed discrete fibers in a laboratory setting. The research aimed to assess the stress-strain-strength properties of sand specimens reinforced with polypropylene fibers. The investigation examined various lengths of fibers reaching up to 50 mm and thicknesses spanning from 0.023 mm to 0.1 mm, resulting in a wide array of aspect ratios, with the highest reaching approximately 2200. Depending on the specific aspect ratio ranges, fiber-reinforced specimens exhibited either reduced strain or increased strain. The researchers concluded that longer fibers with higher aspect ratios contributed to enhanced strength and strain-hardening characteristics in the sand, making it suitable for use as geomaterial in constructing embankments over soft soils, where significant deformations must be accommodated without compromising strength. Consoli et al. (2009) published results from laboratory drainage standard triaxial tests conducted on sand samples treated with randomly distributed polypropylene fibers in the same year. They stated that, at low cement content, fibre addition significantly increased the triaxial peak strength while the ultimate strength is enhanced much more due to adding fibers to the elevated cement concentrations within the sand.

Das et al. (2015) performed studies where pond ash stabilization with various percentages of Guar gum showed improvements in the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). Additionally, the UCS increased through the addition of the biopolymer. Dehghan et al. (2018) performed compaction tests at different concentrations of the biopolymer and found that as the concentration of biopolymers was increased, MDD decreased in conjunction with OMC increasing.

Ayeldeen et al. (2017) studied the addition of guar gum, a natural biopolymer, in enhancing soil stability for geotechnical applications. The research focuses on guar gum's ability to act as an effective binding agent, significantly reducing soil permeability and increasing cohesion among soil particles.

The outcomes demonstrate that adding guar gum to soil improves its structural integrity, making it less prone to erosion and more resistant to deformation under stress. This sustainable approach highlights guar gum's potential as an environmentally-friendly approach for soil stabilization, particularly beneficial for applications requiring reduced soil permeability and increased resilience against environmental factors. Hamza et al. (2023) examined the behavior of subgrade soil stabilized with GG biopolymer, emphasizing its effectiveness as a green and sustainable soil stabilizer. GG treatment increases soil consistency limits and OMC while reducing MDD, indicating its ability to alter soil compaction behavior. The stress-strain behavior improved significantly, highlighting enhanced ductility and better load-bearing capacity with increased GG content and aging periods.

In light of rising carbon emissions from the construction industry, there is an urgent need to explore and develop new sustainable materials for construction purposes. Bamboo fibers, particularly, have gained popularity for soil stabilization due to their effectiveness and eco-friendly properties in improving soil characteristics. Bamboo fibres in soil enhance its strength, resilience, and capacity to support heavy loads (Okubo et al. 2004; Xu et al. 2014). The use of sustainable materials in geotechnical applications is rising as awareness grows regarding their impact on the environment and future generations. Bamboo, a readily available geosynthetic material, possesses a strength comparable to steel (Xu et al. 2014).

Additionally, bamboo fibers are accessible, environmentally friendly, and cost-effective, with the ability to absorb and retain moisture. Soil shear strength can be improved through appropriate modifications, achieved by establishing physical connections between particles and forming chemical bonds or cementation among soil particles. Prasad et al. examined the effect of bamboo fibers with lime on the mechanical characteristics of expanding soil. The test results suggested that expansive soil mixed along lime and bamboo fibers exhibited notably improved strength properties compared to untreated soil. It was also observed that the strength of the soil was enhanced by an increase in curing duration. Chen et al. (2022) investigate the mechanical properties and environmental benefits of using bamboo fiber-reinforced composites in soil stabilization.

This research focuses on enhancing the binding between bamboo fibers and soil through specific treatment methods, aiming to improve soil strength and durability for construction applications. Environmentally, using bamboo fibers, a renewable and biodegradable resource, reduces the environmental impact compared to synthetic materials commonly used in soil reinforcement, making this a more sustainable approach. Jana (2023) used bamboo fiber as a geosynthetic substance for the stabilization of expansive soil. The CBR values began to increase after adding the bamboo fibers into the soil, paving the way to reducing the thickness of the pavement layer.

Similarly, vetiver is a perennial grass that possesses a large and strong rooting system. Fiber extracted from the roots of vetiver has gained immense interest in recent times because of its excellent properties and applications in soil stabilization and erosion control. Vetiver fiber contains around 45% to 55% cellulose and primarily comprises cellulose, hemicellulose, and lignin (Oshunsanya & Aliku, 2017). Several studies have examined the significance of vetiver fiber addition to improve the mechanical properties of the soil, such as its shear strength, bearing capacity, and resistance to deformation concerning the elements such as fiber content, aspect ratio, and alignment (Truong et al. 2008). The natural polymers in the fibers cause them to be strong, durable, and more resistant to degradation. Vetiver fiber serves as a natural reinforcement material that improves soil mechanical properties, forming a dense, interlocking network within the soil matrix that enhances overall strength and load-bearing capacity (Amiri et al. 2017). Jandyal and Shah (2024) investigated the use of vetiver plant roots to reinforce soil and mitigate erosion, with a focus on slope stabilization. Vetiver roots act as a natural barrier against erosion by anchoring the soil and reducing raindrop impact. Results revealed that vetiver roots significantly improved soil shear strength, particularly in silty clay soils, by enhancing soil cohesion and mechanical properties.

Both vetiver and bamboo are renewable and environmentally friendly materials. They can naturally decompose and are readily available in Arunachal Pradesh.

Moreover, Guar gum serves as a natural biopolymer that effectively binds soil particles and fibers, reducing permeability and increasing cohesion. Being biodegradable and renewable, guar gum also offers a sustainable alternative to chemical stabilizers. This paper addresses the mechanical behavior of poorly graded sandy silt of Arunachal Pradesh by the addition of fibers of bamboo and vetiver blended with guar gum.

The inherent ability of natural fibers to enhance soil shear strength and reduce soil permeability was explored as an eco-friendly approach to soil stabilization. Results of experiments, along with reinforcement mechanisms, are discussed.Arunachal Pradesh, located in the northeastern region of India, is characterized by complex topography, high seismicity, and heavy monsoonal rainfall, making it highly susceptible to soil erosion, landslides, and instability.

The state's challenging environmental conditions, including steep slopes, fragile geology, and limited infrastructure, necessitate innovative soil stabilization techniques to ensure the safety and sustainability of construction projects. Traditional soil stabilization methods, such as mechanical compaction and chemical treatment, often prove inadequate due to the region's dynamic climatic conditions and environmental constraints.

2. Experimental Approach and Methodology

The methodology adopted for this study is structured to ensure the reliability and applicability of the findings to real-world geotechnical conditions. The research was conducted in multiple phases, involving soil sampling, fiber material preparation, laboratory testing, and data analysis.

2.1. Soil Sample Properties

The soil sample was collected from Jote, Papumpare district, Arunachal Pradesh. The collected samples were air-dried and sieved to remove larger particles and organic matter before being used for testing. The physical properties of soil were determined as per IS 2720-A (1985) and have been tabulated in Table 1.

The soil was identified as a poorly graded sandy-silt type based on the Unified Soil Classification System (USCS), which was also found for that area by Anshu et al. (2024). The soil was found to be non-plastic and had a liquid limit of 20.29%.

Table 1. Physical characteristics of untreated soil

Index Properties	Test Result
Sieve Analysis	C_c = 9.15 C_u = 0.59
Max. Dry density (g/cc)	1.68
OMC (%)	14.55
Plastic limit (%)	**Non-Plastic**
Liquid limit (%)	20.29
Specific gravity	2.66
Classification (USCS)	**SP-SM**

2.2. Fiber

It is reported that around 60% of India's bamboo resources are in North Eastern States, with Arunachal Pradesh holding the highest concentration. In this rugged terrain region, vetiver grass is most important for stabilizing soil and preventing landslides, especially during heavy rainfalls.

The fibers of the bamboo and vetiver were collected from the NIT Arunachal Pradesh campus. In this study, the fibers utilized were 6 mm long and 0.1 mm in diameter, resulting in an aspect ratio of 60 between length and thickness, as illustrated in Figure 1.

The Energy Dispersive Spectroscopy (EDS) technique was applied to the chemical compositions of bamboo and vetiver fibers, which are portrayed in Figures 2 and 3, respectively.

(a)

(b)

Fig. 1(a) Bamboo fiber, and (b)Vetiver fiber.

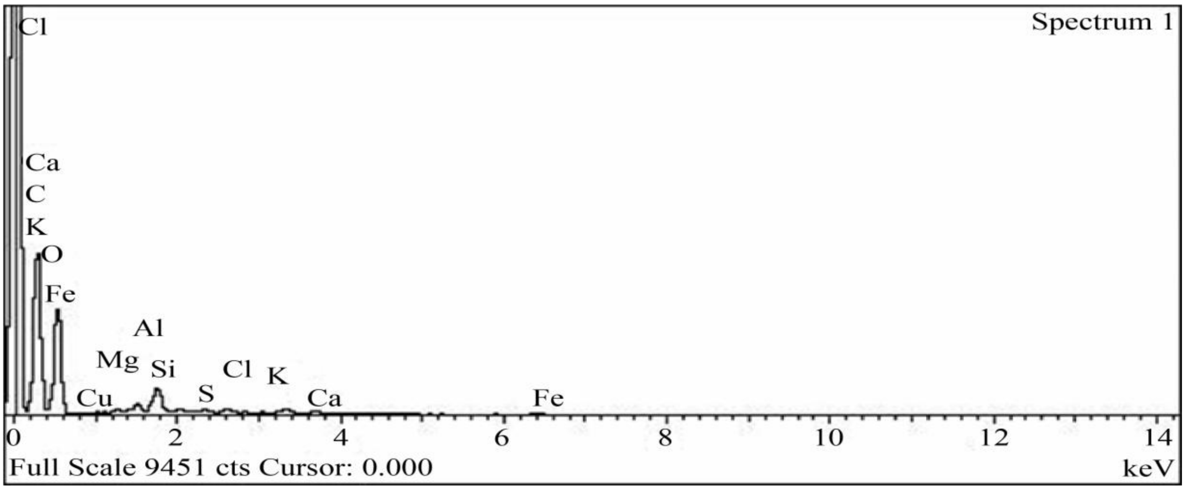

Fig. 2 The chemical compositions of bamboo fiber

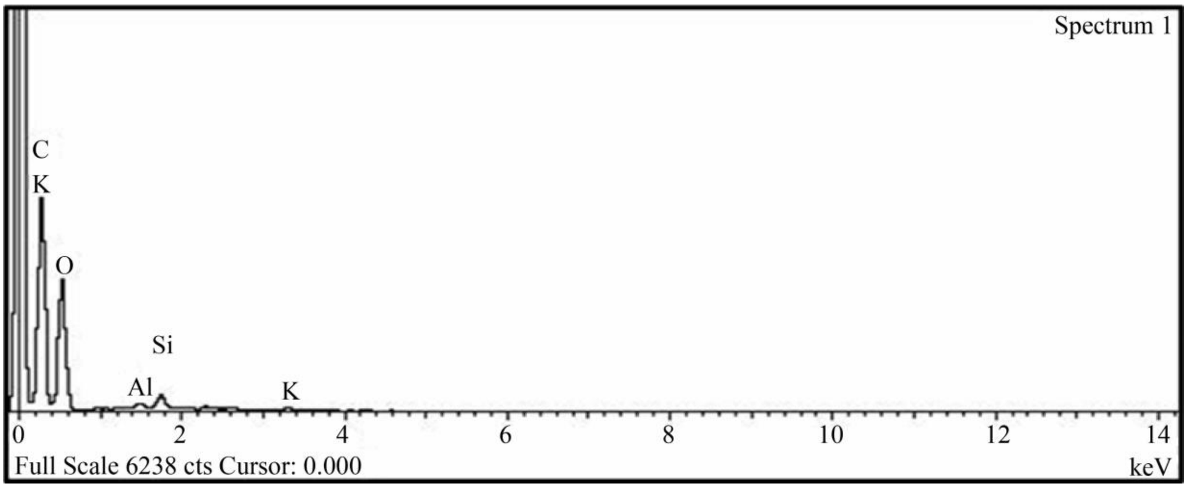

Fig. 3 The chemical compositions of vetiver fiber

Fig. 4 Guar gum powder

2.3. Gaur Gum Powder

Guar gum is a galactomannan polysaccharide from guar beans with unique thickening and stabilizing properties. In the study, the guar gum powder was obtained from Purix Global, Indore, as shown in Figure 4. This biopolymer was chosen on account of its ready availability and affordability when compared to other biopolymers. It also has several other functional properties that are very different and include great solubility in cold water, pH stability, storage stability, compatibility with ionic salts, and pseudo-plastic flow behavior (Ayeldeen et al., 2016).

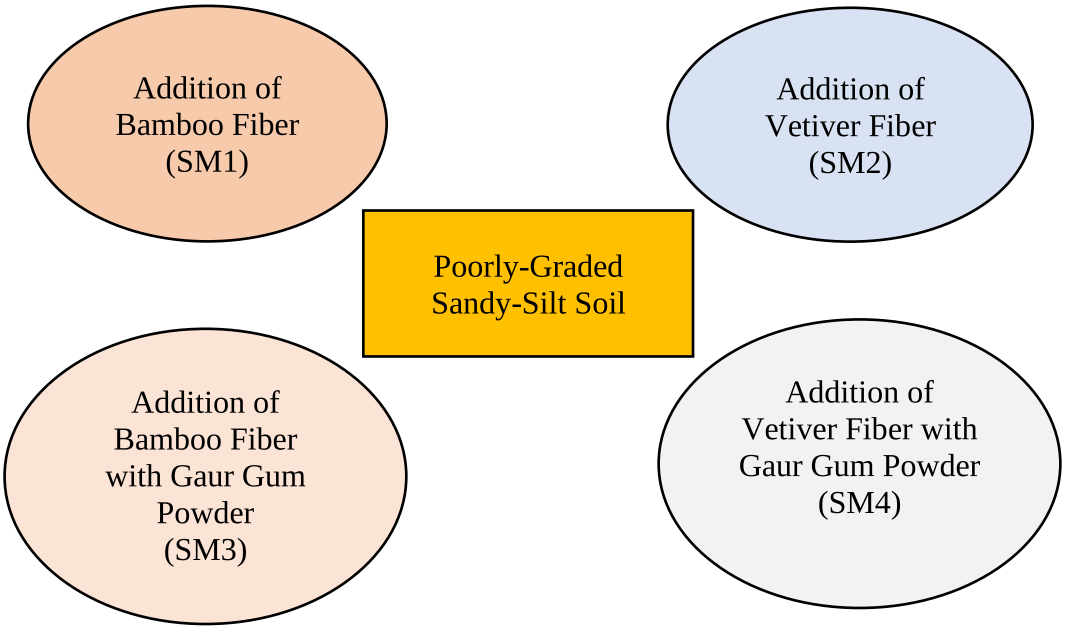

Fig. 5 Different combinations of admixtures mixed with the soil

2.4. Testing Methods

The soil shear strength was performed through Direct Shear test equipment. UU direct shear experiments were conducted on soil specimens under different matric suctions of 0.5, 1, and 1.5 kg.

Figure 5 shows all the mixtures of admixtures added to the poorly graded sandy-silt soil that were tested in this study. A falling head permeability test was also performed to determine the permeability of the poorly graded sandy soil.

2.5. Sample Preparation

To determine the Optimum Moisture Content (OMC), Standard Proctor compaction tests were executed for treated soil. Samples were prepared in four stages: (1) addition of bamboo fibers (S1), (2) addition of vetiver fibers (S2), (3) addition of bamboo fibers with guar gum powder (S3), and (4) addition of vetiver fibers with guar gum powder (S4). Both the fibers and GG powder were added at 1% and 2% by weight of the soil.

3. Result and Discussion

3.1. Effect of Fibers in the Optimum Moisture Content of Soil

Prior to the mix, an optimization for the addition of fibers was conducted. No such changes were observed when the fibers were added at 0.5%. When the percentage was increased to 1 and 1.5, a similar trend of improvement was observed. Further, when the percentage was increased to 2%, a significant decrease in the OMC was noted.

However, when the percentage was increased to 2.5%, an increase in the OMC was observed. Therefore, both types of fibers were added at 1% and 2% by weight of the soil. The impact of adding fibers and GG powder in the OMC of the soil sample is tabulated in Table 2.

Table 2. OMC was obtained by the inclusion of bamboo and vetiver fiber along with GG powder into the soil

Admixtures	OMC (%)	
	Addition of Fibers and Gaur Gum Powder	
	1%	2%
S1	14.20	14.05
S2	14.22	13.80
S3	13.15	13.0
S4	13.25	12.88

A negligible modification in the OMC was found by including 1 and 2% of fibers by weight of the soil when the soil was mixed with bamboo and vetiver fibers, as shown in Table 2.

However, when the fibers were mixed with GG powder, there was a notable decrease in the OMC of the soil. This is attributed to the fact that the GG powder facilitated the fibers to bind together with the soil grains, resulting in the reduction of the moisture content of the soil.

Also, increasing GG powder content from 1% to 2% enhanced the cementitious bonding between soil particles and fibers, significantly leading to the densification of the soil.

3.2. Influence of Fibers and Gaur Gum Powder on Shear Strength Parameters of Treated Soil

With the OMC determined by S1, S2, S3 and S4 at 2% of fiber content and GG powder, the Direct Shear Test (DST) was conducted to ascertain the shear strength characteristics (cohesion, c, and angle of friction, φ) of the treated soil. The effect of adding fibers on the shear strength parameters of the treated soil was determined and displayed in Figure 6.

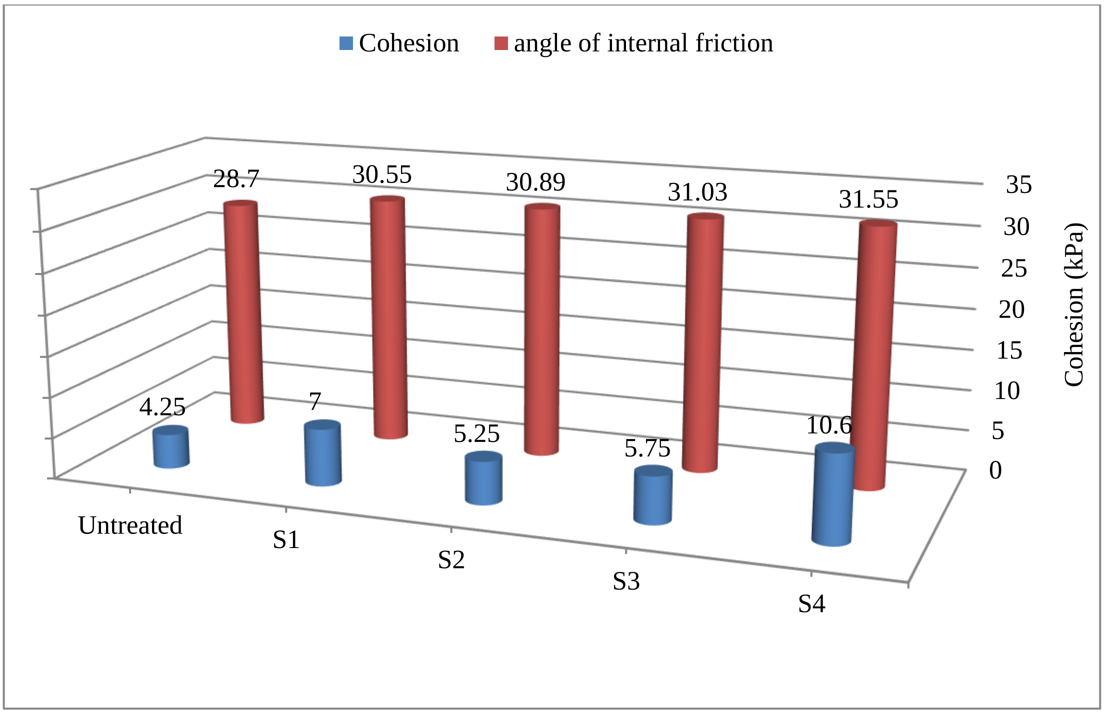

Fig. 6 Influence of the addition of fibers along with GG powder on c and Φ of different soil mixes

From the findings of Figure 6, it was observed that although the inclusion of fibers had improved the shear strength parameters of the treated soil, the addition of GG powder along with fibers showed a notable improvement. The cohesion of untreated soil, which was 4.25 kPa, improved to 5.75 kPa and 10.6 kPa when the soil was treated with bamboo fiber, GG powder, vetiver fiber and GG fiber, respectively. Fibers can interlock better within the soil matrix, enhancing the overall structural integrity. They provide greater tensile strength, which can help distribute loads more evenly across the soil. The texture of the bamboo and vetiver fibers influences how well they bond with soil particles. Fibers with a rough surface can create more friction and enhance the bonding capacity, improving soil strength. The GG powder, which acted as a cementitious powder, helped the fibers to form an effective bonding between the soil grains. Moreover, the bamboo and vetiver fibers absorbed the moisture from the soil, making it more compact to withstand loads.

3.3. Effect of Fibers and Gaur Gum Powder on the Permeability of Treated Soil

The samples were prepared by adding 2% of fibers and GG powder by weight of water content and kept undisturbed for 7, 14 and 28 days. After the completion of respective days, the water was permitted to flow for 24 hours, and the head differences were noted. The variations in permeability of the untreated soil and treated soil mixes after the respective reaction period are given in Table 3.

Table 3. Permeability test values for treated and untreated soil

Condition	**Permeability, k (cm/s)**		
Untreated Soil	$6.59 * 10^{-3}$		
Reaction Period (days)	**7**	14	28
Treated Soil	$5.72 * 10^{-3}$	$4.52 * 10^{-3}$	$4 * 10^{-3}$

From the experimental results, as elaborated in Table 3, it was seen that the permeability of soil has reduced as the reaction period increases. The permeability of natural soil was 6.59×10^{-3} cm/s, which was reduced to 5.72×10^{-3} cm/s, 4.52×10^{-3} cm/s, and 4×10^{-3} after a reaction period of 7, 14 and 28 days respectively. With time, the fibers and the GG powder form an effective bridging between the soil gains. The interaction among the fibers and GG powder in the soil leads to densification that removes the voids. The fibers, bamboo and vetiver utilized GG powder as a cementation source, compacting the soil that restricts the pore openings in the soil.

4. Practical Significance Criteria for Soil Stabilization

To assess the effectiveness of the soil stabilization approach, significance is determined based on practical geotechnical performance indicators rather than statistical measures.

These criteria ensure that the improvements in soil properties are meaningful for real-world applications, particularly in Arunachal Pradesh's challenging environmental conditions. The information is presented in a tabular format for clarity in Table 4.

Table 4. Practical significance criteria for soil stabilization

Parameter	Significance Criteria	Practical Interpretation
Shear Strength (Cohesion & Friction Angle)	Cohesion should increase by at least 25%, and friction angle should improve by 2-5° compared to untreated soil.	If cohesion and friction angle improve significantly, the stabilization method effectively enhances soil strength.
Permeability Reduction	Permeability should decrease by 30-40% over 28 days, indicating better water retention and reduced erosion potential.	Further optimization (e.g., adjusting fiber ratio or binder content) is required if permeability remains high despite treatment.
Optimum Moisture Content (OMC) & Maximum Dry Density (MDD)	The OMC should decrease, while the MDD should increase or remain stable, indicating better compaction without excessive water demand.	If OMC is too high, the soil may require excessive water for compaction, reducing efficiency. A higher MDD suggests better compaction.
Fiber Content Effectiveness	1-2% fiber addition is considered optimal; >2% may lead to uneven distribution, reducing effectiveness.	If fiber content exceeds 2%, the soil may become difficult to work with, leading to inconsistent stabilization results.
Long-Term Stability	The treated soil should maintain its strength and reduced permeability after 28 days.	If soil strength deteriorates over time, it may not be suitable for long-term stabilization and requires further modification.

5. Conclusion

In this research, based on fiber inclusion, a solution for poorly graded sandy soil was examined. The addition of fibers along with GG powder resulted in a decrease in OMC, resulting in enhanced shear strength of the soil. The combination of fibers and GG showed promising results in improving soil properties, with bamboo fibers demonstrating notable effectiveness on the poorly-graded sandy soil due to their mechanical strength and water absorption capacity. The cohesion of untreated soil increased significantly after treatment. With the addition of bamboo fiber and GG powder, cohesion improved by approximately 35% for bamboo fiber treatment and 150% for vetiver fiber treatment. Permeability reduced progressively over time. Initially, untreated soil had a permeability of 6.59×10^{-3} cm/s. After 28 days of treatment with fibers and GG powder, the permeability was 4×10^{-3} cm/s, marking a reduction of approximately 39%. The inclusion of vetiver and bamboo fiber with GG powder has the potential to serve as a nucleating agent, hence exerting control over the binding process.

The optimum content of fibers and GG powder is crucial to achieving the ideal mix between strength, durability, and environmental sustainability. Higher fiber proportions (>2%) cause uneven distribution and weaken the soil matrix. Additionally, GG content above 2% can cause excessive soil stiffness, crack while drying, or swelling in the presence of water, which would decrease the overall stability of the soil. In the study, the combination of 2% fiber content with 2% GG powder resulted in maximum shear strength, as GG improved the interlocking and tensile properties of the fibers. Beyond this, strength may be decreased by the addition of excessive amounts of GG or fibers that hinder effective particle interaction.

Moreover, vetiver and bamboo fibers are renewable and environmentally friendly due to their rapid growth compared to other natural fibers. These fibers can naturally decompose, contributing to maintaining clean air and water. Therefore, using bacteria, vetiver, and bamboo fibers indicates its potential as a green technology with significant strategic importance for the future. Having this understanding would facilitate the advancement of natural fibers to attain their maximum efficiency. Further research can be conducted to scale up to high-level field applications and accurately predict outcomes in the challenging and realistic natural environment. Further research is required to explore various fiber lengths, aspect ratios, and orientations to comprehensively assess the impact of fiber inclusion on the treated soils.

5.1. Future Work and Implications

The findings of this study have significant implications for sustainable geotechnical engineering, particularly in regions like Arunachal Pradesh, where environmental considerations are paramount. The successful utilization of natural fibers such as vetiver and bamboo, combined with biopolymers like guar gum, offers a viable alternative to traditional soil stabilization methods.

5.2. Broader Implications

- Environmental Sustainability: Using renewable and biodegradable materials aligns with global efforts to reduce the environmental footprint of construction activities. Natural fibers and biopolymers decompose without leaving harmful residues, thereby minimizing ecological impact.
- Economic Viability: Implementing locally sourced materials such as vetiver and bamboo can lead to cost savings in soil stabilization projects. This approach

reduces material costs and supports local economies through the cultivation and processing of these plants.

- Enhanced Soil Properties: Incorporating natural fibers has been shown to improve soil shear strength and reduce erosion. For instance, vetiver roots significantly enhance the shear strength parameters of the soil-root matrix, contributing to better slope stability.

5.3. Recommendations for Future Research

- Long-Term Performance Studies: While initial results are promising, long-term field studies are necessary to assess the durability and performance of fiber-reinforced soils under varying environmental conditions.
- Optimization of Fiber Treatment: Investigate the effects of different treatment methods on natural fibers to enhance their durability and interaction with soil particles. This could involve chemical or physical modifications to improve fiber-soil bonding.
- Comprehensive Environmental Impact Assessments: Conduct life cycle assessments to fully understand the environmental benefits and potential trade-offs associated with large-scale natural fiber-based soil stabilization implementation.
- Development of Design Guidelines: Establish standardized protocols and design guidelines for engineers to effectively implement natural fiber and biopolymer soil stabilization techniques in various geotechnical applications.

Future research can further validate and refine using natural fibers and biopolymers in soil stabilization by addressing these areas promoting more sustainable and effective engineering practices.

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Author Contributions

RPB: Writing-Original preparation, Formal analysis, Revision and editing of the drafted manuscript; AKA: Conceptualization, Formal analysis, Writing-Original preparation, Revision and Editing of the drafted manuscript.

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