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Bamboo as a Geogrid Material for Enhanced Slope Stabilization

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ABSTRACT: Bamboo (*Bambusoideae*) was developed as a sustainable alternative to synthetic geogrids for use in slope stabilization due to its high mechanical strength, rapid renewability, and low environmental footprint. This research examined the performance of non-treated *Gigantochloa scortechinii* (Buluh Dinding) bamboo as geogrid reinforcement in clay loam soil, which was a widely open area of critical tropical soil applications. The results confirmed that bamboo geogrid reinforcement increased soil stability, with the shear resistance rising from 31 kPa in unreinforced soil to 65 kPa in reinforced soil. In addition, the introduction of two-layer bamboo geogrids decreased soil consolidation by 50.46%, demonstrating better performance compared to the use of single-layer bamboo geogrids. Mechanical tests showed that bamboo specimens with larger diameters (7 cm) and bricks of optimal thickness (1.5 cm) supported compressive stresses of up to 1152.29 MPa, proving their structural suitability for geotechnical purposes. These results emphasized that bamboo was a successful eco-friendly geogrid material capable of replacing mineral alternatives and facilitating green infrastructure development. It offered valuable insights for adopting bamboo-based solutions in slope stabilization in areas exposed to challenges of soil instability and erosion.

KEYWORDS: Bamboo; geogrid; slope stabilizatin; soil stability

1. Introduction

Slope stabilization remained one of the critical issues in geotechnical engineering, especially in tropical countries where unstable soil traditionally caused erosion and degradation of essential infrastructure. Synthetic geogrids had been extensively used for soil reinforcement [1], although their negative environmental impact created an urgent need for alternatives due to their high carbon footprint and non-biodegradable nature. Bamboo (*Bambusoideae*) emerged as an excellent option, with superior mechanical characteristics, rapid renewability, and complete biodegradability [2]. Nevertheless, overall research on bamboo behavior as a geogrid in tropical soils was relatively limited, particularly concerning its long-term performance and the lack of standardized application protocols.

This research gap was addressed in this study through a systematic investigation of *Gigantochloa scortechinii* (locally known as Buluh Dinding), a bamboo species native to Southeast Asia with demonstrated structural potential [3]. The study focused on its use in strengthening clay loam soils—common yet challenging tropical soils known for their low shear strength (25–35 kPa) and significant settlement potential [5]. While earlier studies primarily investigated treated bamboo composites, this study evaluated untreated bamboo to assess its natural performance and reduce processing demands.

The experimental approach was based on standardized ASTM protocols to ensure strict reproducibility of results. The structural capacity of bamboo was determined using compression tests (ASTM D695), while soil reinforcement effects were quantified using vane shear tests (ASTM D2573) and consolidation tests (ASTM D2435). Additional insights were obtained through moisture content analysis (ASTM D2216) to understand soil–bamboo interactions under typical tropical conditions. This comprehensive approach enabled direct comparison with conventional geogrid materials while accounting for regional environmental contexts.

Preliminary analysis showed that bamboo provided a dual reinforcing mechanism: shear resistance in geogrid structures was enhanced through particle interlocking, while settlement was reduced via improved load distribution. These findings not only confirmed the technical feasibility of bamboo but also highlighted its potential to outperform synthetic counterparts in both ecological and economic aspects. The aim of this study was to establish performance benchmarks for untreated bamboo geogrids in tropical soils, thereby laying the groundwork for developing sustainable and eco-friendly slope stabilization practices aligned with global environmental goals.

2. Materials and Methods

2.1. Preparation of materials.

The materials used in this study included local bamboo, *Gigantochloa scortechinii*, commonly known as Buluh Dinding, which was sourced from the Nyirubulat Kraftangan Store in Kelantan. The soil sample used for the experiments was clay loam soil collected from Kampung Gerisek, Bukit Gambir, Muar, Johor. This soil was filled into a plastic box model with dimensions of 55 cm × 35 cm × 45 cm, reaching a height of 35 cm (Figure 1).

(a) (b) (c)

Figure 1. (a) Dinding bamboo; (b) Clay loam Soil; (c) Plastic box model.

2.2. Methodology development.

The methodology of this study aimed to evaluate the effectiveness of *Gigantochloa scortechinii* (Buluh Dinding) bamboo as a geogrid reinforcement material for soil stabilization. The bamboo's mechanical properties were assessed through compression strength testing (ASTM D695), where the bamboo's performance under compressive forces was measured [6]. In parallel, the soil moisture content (MC) of clay loam was determined following ASTM D2216. The test was conducted over a 24-hour period to evaluate the soil's water retention capacity and the effect of moisture on its behavior when reinforced with bamboo [7]. Shear strength tests were then conducted on the clay loam soil using ASTM D2573 (Vane Shear Test), which helped assess the changes in shear strength with and without bamboo geogrid reinforcement [8]. Subsequently, settlement monitoring was carried out using a Linear Variable Differential Transformer (LVDT) system in accordance with ASTM D2435. This test was conducted over a three-day period to observe soil settlement behavior under the influence of one and two layers of bamboo geogrid reinforcement [9]. These tests were designed to assess the impact of bamboo on the mechanical and physical properties of clay loam soil, providing valuable insights into its potential as a sustainable and cost-effective solution for soil stabilization in geotechnical applications [10]. While the experimental model offered controlled insights into bamboo geogrid performance, it did not fully replicate real slope conditions, such as variable soil layers, groundwater fluctuations, and large-scale environmental stresses. This limitation was considered when interpreting the findings.

2.3. Compression strength test.

Three bamboo samples of varying sizes were collected to determine their mechanical properties, specifically their compression strength (Figure 2). Bamboo A had a diameter of 7 cm and a thickness of 1 cm; Bamboo B had a diameter of 6 cm and a thickness of 2 cm; and Bamboo C, the largest specimen, had a diameter of 7 cm and a thickness of 1.5 cm [11]. The primary objective of the compression strength test was to assess the behavior of each bamboo specimen under a compressive load using a Universal Testing Machine (UTM Instron). The load was gradually applied until failure occurred, and the failure modes, whether end bearing or splitting, were analyzed. Parameters such as load (kN) and strength (MPa) were recorded during the test. Testing was conducted in accordance with ASTM C39/C39M-09a standards [12].

Figure 2. Bamboo samples A, B, and C, each with a height of 150 mm.

2.4. Soil Sample.

Clay loam soil was collected from Kampung Gerisek, Bukit Gambir, Muar, Johor, for testing its moisture content (MC%) [7]. The MC% of the soil was determined through a drying process in a dry oven, in accordance with MS 1056-2:2005 standards. The clay loam soil, characterized by its dark brown color, relatively firm texture, and moderate moisture content, exhibited good water retention properties. The soil's texture, with a balanced proportion of sand, silt, and clay, provided a suitable medium for evaluating moisture content, which is essential for understanding its behavior in various geotechnical applications [7].

2.5. Preparation of the Bamboo Geogrid Model.

The model preparation involved a controlled setup with three variations: a model without bamboo geogrid reinforcement (Model A), a model with one layer of bamboo geogrid reinforcement (Model B), and a model with two layers of bamboo geogrid reinforcement (Model C). Bamboo samples were cut into strips, each with a width ranging from 10 to 15 mm, and arranged in grid positions resembling a biaxial geogrid for use as soil reinforcement (Figure 3 and Table 1). The rib dimensions, aperture size, and thickness of the bamboo geogrid were measured to ensure consistency and accuracy in the model setup [10].

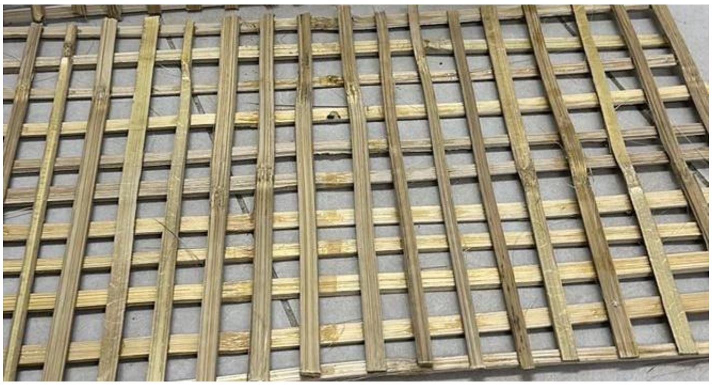

Figure 3. Preparation of Bamboo Geogrid

Table 1 Characteristics of Prepared Bamboo Geogrid

Characteristics	Value
Aperture (mm x mm)	15 x 15
Thickness (mm)	2
First layer area of the geogrid (m x m)	0.55 x 0.35
Second layer area of the geogrid (m x m)	0.53 x 0.33

2.6. Van shear test.

In this study, the field vane shear test was conducted to assess the shear parameters of the soil sublayer, following ASTM D2573 standards. A rectangular vane with a height of 50 mm and a diameter of 25 mm was used for the test. This vane size was selected due to its sensitivity, considering the high water content and compressibility of the soil. The dimensions of the vane were chosen based on the consistency of the soil during testing [6].

2.7. Monitoring of Settlement

Settlement monitoring was carried out over a three-day period to evaluate the behavior of soil under different reinforcement conditions (Figure 4). These included an unreinforced control model (Model A), soil reinforced with one layer of bamboo geogrid (Model B), and soil reinforced with two layers of bamboo geogrid (Model C). Data collection was performed using a data logger connected to a Linear Variable Differential Transformer (LVDT) and a 15 kg loading plate, ensuring accurate and consistent measurements. For Model B, the bamboo geogrid was positioned approximately 5 cm below the surface of the soil layer, while for Model C, the second layer of bamboo geogrid was placed 10 cm from the soil surface [6].

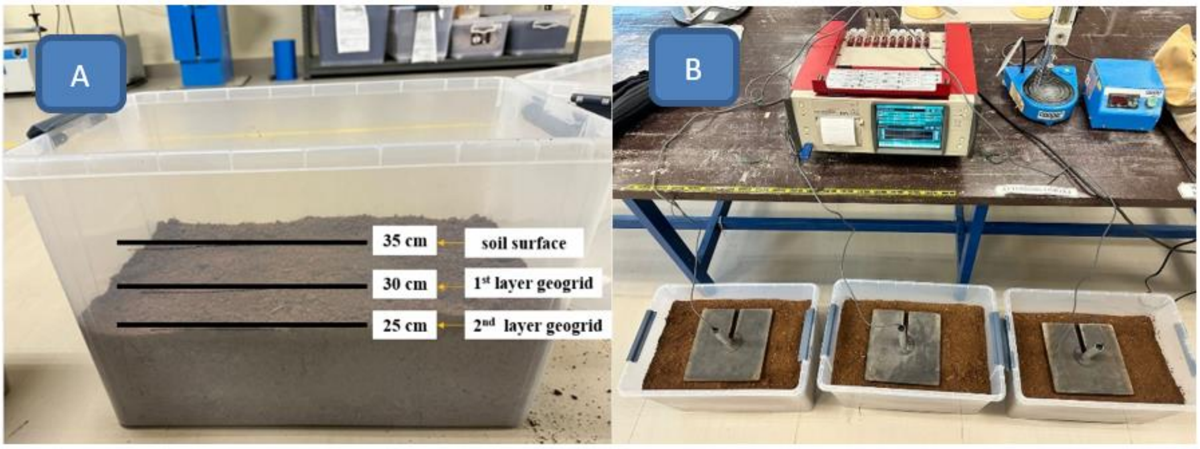

Figure 4. (a) Height placement of two-layer bamboo geogrid; (b) Setup with LVDT, data logger, and 15 kg loading plate.

3. Results and Discussion

3.1. Compressive strength test.

In order to systematically evaluate the compressive characteristics of bamboo samples, standardized testing (ASTM D695) was used, and all have shown characteristic failure modes of end-bearing (grinding) failure. This type of failure manifested in a form of localized cracking at the points of load application (Figure 5) as expected for the standard response of bamboo in cylindrical form to axial loads. Quantitative analysis showed considerable differences in the performance of mechanics among different specimens with various configurations of geometry (Table 2). Specimen C (7 cm diameter x 1.5 cm thick) had an optimum performance whereby the peak ratio compressive stress attained with 76599.73 N of applied force was 1152.29 MPa. This is a 22.4% strength improvement from Specimen B (6 cm diameter, 2 cm thickness) that had the lowest values (925.77 MPa at 64,246.87 N), even though that specimen had higher wall thickness. The results show that diameter indeed has a greater effect on load-bearing capacity than thickness alone since, Specimen A (7 cm diameter, 1cm thickness) has intermediate performance (1133.71 MPa at 72,123.19 N) when compared to its thiniest walls.

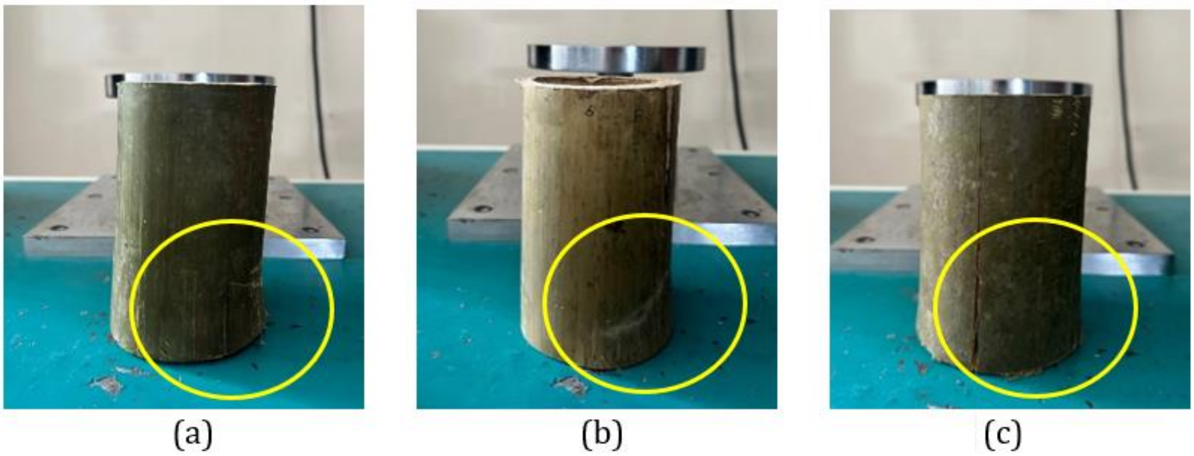

Figure 5. Cracks in Bamboo After CS Test (in yellow) (a) Bamboo A; (b) Bamboo B; (c) Bamboo C

Table 2. Compression strength test results.

Bamboo	Time (min)	Elongation (mm)	Force (N)	Compression Stress (MPa)	Strain (%)
A	1.638	7.09	72123.19	1133.71	4.663
B	1.359	5.61	64246.87	925.77	3.74
C	1.546	6.71	76599.73	1152.29	4.531

These results advanced the current understanding of bamboo mechanics in three key areas. First, the superior performance of Specimen C confirmed the existence of an optimal thickness-to-diameter ratio (approximately 0.21 for this species), as predicted by theoretical models proposed by Handana et al. [12]. This ratio optimized material efficiency and prevented wall buckling. Second, contrary to conventional expectations, the greater thickness of Specimen B did not compensate for its smaller diameter, demonstrating that cross-sectional area was the predominant factor in determining compressive resistance. This observation aligned with the size-effect principles found in anisotropic natural materials [14]. Third, all specimens exhibited a consistent end-bearing failure mode characterized by longitudinal splitting rather than lateral deformation, indicating that the compressive behavior of bamboo was governed by its vascular structure. This finding supported the microstructural analysis by Marzuki and Zainorabidin [5], who identified fiber bundle distribution as the dominant variable influencing compression resistance. Further clarification of these relationships was provided by the strain patterns. Specimen C exhibited balanced deformation characteristics (4.531% strain), compared to the excessive elongation of Specimen A (4.663%) and the limited deformation of Specimen B (3.74%). This ideal strain behavior corresponded with the efficient stress distribution observed in geogrid applications, where controlled deformation is critical for effective soil reinforcement performance.

3.2. Moisture content test.

The clay loam soil specimens, similar to those used in this study, were oven-dried for 24 hours at 105°C to determine their natural moisture content (MC). This drying method is a standard procedure for accurately measuring soil moisture, ensuring that the results reflected the true amount of water present in the soil prior to any testing or treatment. After the drying process, the MC was calculated as a percentage of the soil’s dry weight. This procedure provided a reliable measure of the soil’s natural moisture content, which was essential for understanding its properties and behavior in various geotechnical applications (Table 3).

Table 3. Moisture content test.

Soil Sample	Can Weight (m_1)	Can Weight + Wet Soil (m_2)	Can Weight + Dry Soil (m_3)	Mass of Water ($m_4 = m_2 - m_3$)	Mass of Dry Soil ($m_5 = m_3 - m_1$)	Moisture Content (%)
Soil A	18.8	64.5	56.1	8.4	37.3	22.5
Soil B	19.8	56.9	49	7.9	29.2	27.1
Soil C	20.3	56.1	48.1	8	27.8	28.8

$$Average\ Moisture\ Content = \frac{22.5\% + 27.1\% + 28.8\%}{3}$$

$$= 26.13\%.$$

The moisture content (MC) test conducted on the soil sample resulted in an average value of 26.13%, which falls within the typical range for clay loam soils and indicates a moderate water-holding capacity. This value reflects the balanced composition of clay, silt, and sand characteristic of clay loam, suggesting that the soil retains sufficient moisture in its natural, unsaturated state. These findings support the classification of the soil as clay loam, a type known for maintaining moisture levels suitable for agricultural and structural applications. The results are consistent with prior research, such as a study conducted in Bely Yar, which reported MC values ranging from 15.5% to 26.3%, with a maximum of 27.3% using both microwave and convection oven drying methods. Although some variability was observed among individual samples (22.5%, 27.1%, 28.8%), the overall findings align well with moisture content ranges reported in similar studies, reinforcing the soil's classification as clay loam [7].

3.3. Vane shear test.

The Vane Shear Test (VST) was used to evaluate the shear strength of cohesive soils, particularly soft and fine-grained types such as clay, following ASTM D2573 standards. The results, shown in Table 4 and Table 5, revealed variations in shear strength under different conditions and reinforcement models. The average shear strength, Cu, before the placement of bamboo geogrid reinforcement was recorded at 31 kPa. After the bamboo geogrid was placed, the average Cu increased slightly to 34 kPa, indicating a modest improvement in soil shear strength due to the reinforcement. This suggested that while the bamboo geogrid did not drastically alter the shear strength of the soil, it contributed to a slight improvement. The bamboo geogrid also effectively reduced deformation when load was applied, indicating its potential to enhance the stability of the soil structure. The significance of these findings relative to prior studies included an increase in shear strength from 20 kPa to 21 kPa after bamboo geogrid reinforcement, which aligned with previous research on peat soil [10]. Although the increase was modest, it demonstrated the positive impact of bamboo geogrids on soil stability. Additionally, bamboo geogrids effectively reduced soil settlement, highlighting their potential as a sustainable solution for geotechnical applications.

Table 4. VST results before bamboo geogrid reinforcement installation.

Location	Shear Strength, Cu (kPa)
Left	30
Middle	32
Right	30
Average	**31 kPa**

Table 5. VST results after bamboo geogrid reinforcement installation.

Location	Shear Strength, Cu (kPa)
Left	34
Middle	34
Right	33
Average	**34 kPa**

3.4. Soil settlement monitoring.

In summary, during the monitoring period, Model A, without any reinforcement, experienced the highest settlement of 2.89 mm due to the direct application of the load on the soil, which caused significant compression and deformation. In contrast, Model B, with one layer of bamboo geogrid, showed a notable improvement with a settlement of 2.29 mm, reflecting a reduction in displacement by 20.76%. Model C, reinforced with two layers of bamboo geogrid, performed the best, with a reduced settlement of only 1.496 mm, marking a 48.23% decrease compared to Model A. The bamboo geogrid layers helped distribute the load more evenly, enhancing the soil's stiffness and reducing deformation, demonstrating the effectiveness of bamboo geogrid as reinforcement for controlling soil settlement.

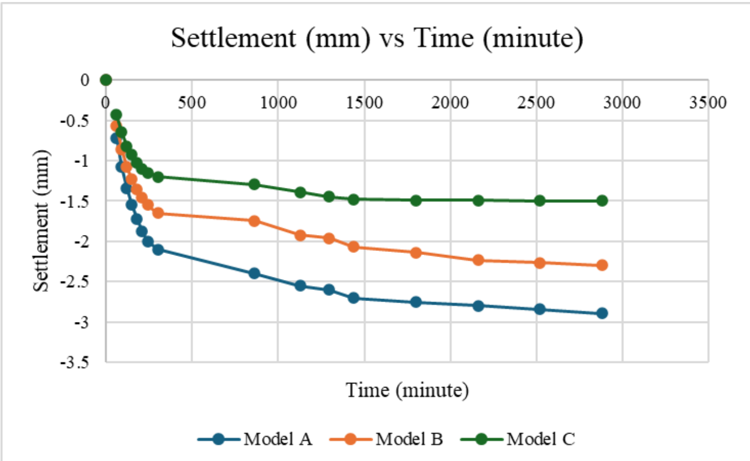

Figure 6. Settlement vs time graph for Model A, Model B, and Model C.

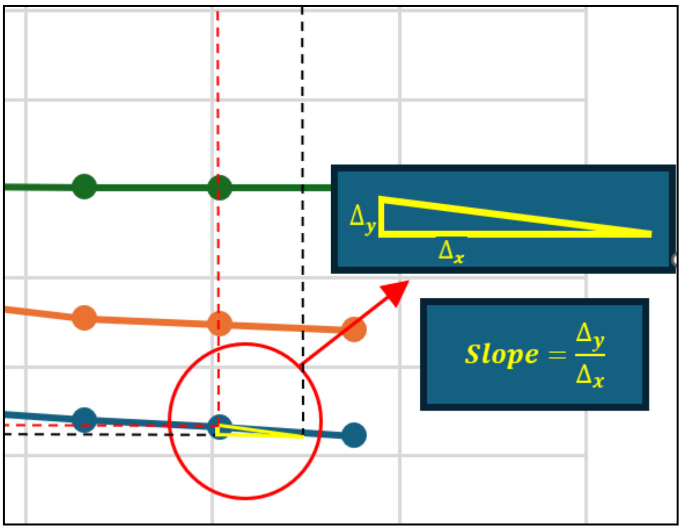

Figure 7. Triangular method for the slope of settlement curves.

$$Model\ A = \frac{-2.92 - (-2.84)}{3000 - 2000} = \frac{-0.08}{1000} = -0.000348\ mm/minute.$$

$$Model\ B = \frac{-2.25 - (-2.18)}{3000 - 2000} = \frac{-0.07}{1000} = -0.000304\ mm/minute.$$

In Figure 6, the graph showed that the settlement for Models A and B continued beyond 3 days. Therefore, the Triangular Method for the Slope of Settlement Curves was applied to calculate their final settlements, as shown in Figure 7. This method effectively estimated the long-term settlement behavior. After 3 days, settlement continued but at a very slow rate. As time progressed toward equilibrium ($t \rightarrow \infty$), the settlement was estimated to increase slightly by approximately −0.1 mm for Model A and −0.05 mm for Model B. For both models, the slow settlement rates (−0.000348 mm/minute for Model A and −0.000304 mm/minute for Model B) indicated that settlement persisted over time but at a decreasing rate. These rates were used to calculate the additional settlement, leading to the final estimated values of −3.02 mm for Model A and −2.30 mm for Model B, while Model C stabilized at −1.496 mm (Table 6 and Table 7).

Table 6. Settlement monitoring results for three models over three days.

Day	Time	Model A	Model B	Model C
1	10:30 am	-17.262	-16.182	-17.622
2	10:30 am	-18.818	-17.18	-18.62
3	10:30 am	-20.152	-18.478	-19.118

Table 7. Settlement comparison for different models with bamboo geogrid reinforcement.

Settlement for Controlled Model (Model A)	Settlement for One-Layer Bamboo Geogrid (Model B)	Settlement for Two-Layer Bamboo Geogrid (Model C)	Difference in Settlement of Model A and Model B (%)	Difference in Settlement of Model A and Model C (%)
3.02 mm	2.30 mm	1.496 mm	23.84%	50.46%

The results demonstrated that bamboo geogrid reinforcement effectively reduced soil settlement, with the control model experiencing the greatest deformation. Model C, which utilized two layers of bamboo geogrid, showed the most significant improvement by substantially minimizing settlement. Bamboo geogrids enhanced soil performance by distributing applied loads, reducing stresses, and increasing stiffness, thereby offering a sustainable and cost-effective solution for improving soil stability and load-bearing capacity. These findings aligned with prior studies: similar trends were observed where bamboo geogrid reinforcement significantly reduced settlement. For example, an earlier study reported reductions from 0.335 cm (Model A) to 0.253 cm (Model B) and 0.201 cm (Model C) [10], while the current study showed reductions from 3.02 mm (Model A) to 2.30 mm (Model B, a 23.84% reduction) and 1.496 mm (Model C, a 50.46% reduction). The consistent results across studies confirmed the effectiveness of bamboo geogrids, particularly with multiple layers, in reducing soil settlement and enhancing stabilization [10].

4. Conclusions and Recommendations

This study showed that untreated Gigantochloa scortechinii bamboo geogrids provided a technically sound and ecologically viable solution for slope stabilization in clay loam soils.

The experimental results demonstrated that the geometric parameters governed the compressive strength of bamboo, with optimum performance achieved at a diameter of 7 cm and a wall thickness of 1.5 cm, reaching an impressive compressive stress of 1152.29 MPa. The bamboo geogrid system substantially improved soil stability through two major mechanisms: increasing shear strength from 31 to 34 kPa (a 9.7% increase) by enhancing particle interlocking, and decreasing settlement by up to 48.23% in two-layer configurations via effective load distribution. These performance metrics compared favorably against conventional synthetic geogrids while offering superior environmental benefits such as full biodegradability and a significantly lower carbon footprint. The results therefore provided strong justification for implementing bamboo geogrids in geotechnical applications, especially in tropical regions where both the material and the target soils are abundant. The research identified critical design parameters for optimal performance and emphasized the importance of cross-sectional geometry in the structural behavior of bamboo. While these laboratory findings were promising, further studies were recommended to assess long-term durability in field conditions and the potential benefits of protective treatments. This work opened a new avenue for environmentally friendly slope stabilization methods that integrate engineering requirements with nature conservation, proposing a functional alternative to traditional slope stabilization techniques by combining engineering criteria with ecological responsibility in infrastructure planning.

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Author Contribution

Each author made an equal contribution to the development of the study, including its conceptualization, methodology, data gathering, analysis, and manuscript preparation. All authors reviewed and approved the final manuscript for submission.

Competing Interest

All authors declare that there is no conflict of interest of this publication.

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