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Sustainable subgrade reinforcement for low-volume roads: Bamboo vs Geosynthetics

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Unpaved roads constructed on weak soil subgrades have often suffered severe damage, necessitating regular maintenance and repairs. While geosynthetics like geogrids and geotextiles have traditionally been used for soil stabilisation, their high cost has driven interest in sustainable alternatives. Bamboo grids have proven to be a viable alternative to synthetic materials for strengthening subgrades in low-volume road applications, offering environmental and economic benefits. Three test sections measuring 50 × 50 sq. cm have been constructed for dynamic cone penetration tests (DCPT) to assess in situ strength and penetration resistance.The effectiveness of bamboo in subgrade stabilisation has been assessed by comparing its performance to that of geogrid, geotextile, and unreinforced soil subgrade.A reduction in DCPI values has been observed in the bamboo-reinforced test sections compared to the unreinforced section. Test results have shown that bamboo grid reinforcement has reduced penetration depth by 65% compared to unreinforced soil and has matched the performance of geotextile reinforcement. These findings from the present study indicate that bamboo grids offer a viable, sustainable replacement for subgrade reinforcement and are locally available.

Keywords: Bamboo grid reinforcement, DCPT, Geogrid, Geotextile, Geosynthetics, Subgrade stabilisation, Unpaved roads

1 Introduction

Rural or low-volume roads connect rural areas, help local businesses and give access to necessary services. Weak subgrade soils often cause these roads to struggle greatly, resulting in regular failures, including rutting, cracking, and settlement[1,2]. Traditionally, engineers have used synthetic geogrids to reinforce these soil subgrades[3]. Geogrids, made from polymers like polypropylene or polyester, improve load distribution and reduce pavement thickness[4]. However, their environmental impact and high costs are the point of concern, prompting researchers to seek more sustainable alternatives.

Bamboo is a rapidly growing and renewable natural resource that has recently drawn attention as a viable alternative to synthetic reinforcements in road construction. The tensile strength of bamboo, ranging up to 630 MPa, and its significant rigidity, characterised by elastic modulus values between (11-17) GPa, make it an exceptional option for subgrade reinforcement. Studies indicate that bamboo grids can enhance soft soils' load-bearing ability and diminish stress deformations[8]. Bamboo sequesters carbon, uses little energy, and is abundant in many poor locations. Bamboo has mechanical, environmental, and socio-economic benefits, especially in natural areas. Bamboo production and harvesting can boost local economies and create jobs, supporting sustainable development[5]. The placement depth of the reinforcement is a crucial parameter for getting the optimum strength[6,7].

Furthermore, using indigenous bamboo reduces transportation expenses and the carbon footprint of importing synthetic materials. Bamboo's physical qualities vary by species, age, and treatment method, and its capacity under adverse environmental circumstances must be addressed in engineering applications. Bamboo upgrading reinforcement has hurdles despite its potential qualities. Durability issues, especially in humid or damp areas, and a lack of defined design requirements have hampered its implementation[8]. While some field trials have demonstrated the effectiveness of the bamboo grid in reducing road reformation and improving service life, there is still a lot left to be uncovered.

This paper addresses the challenge of improving weak subgrade soils in low-volume roads by evaluating the effectiveness of bamboo grid

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reinforcement as a sustainable alternative to conventional geosynthetics, through a critical review of laboratory experiments, existing studies, and field tests (DCPT). This study aims to provide practical insights and evidence-based recommendations for engineers and policymakers seeking sustainable solutions for rural road infrastructure.

2 Materials and Methods

Reinforcement of subgrades in low-volume roads is a vital part of rural infrastructure, particularly in areas where poor soils and scarce resources limit the strength and performance of pavements. Historically, steel and geogrids have been used to improve subgrade strength and minimise deformations[9]. However, cost and environmental issues have stimulated interest in sustainable solutions like bamboo and other natural fibres[4,10].Bamboo mechanical properties, including high tensile strength, flexibility, and fast renewability,have spurred geotechnical and pavement engineering studies. Sulphur-treated bamboo culms can replace steel in low-volume road building due to their modulus of elasticity, compressive, and tensile strength[11]. Later research has shown that bamboo piles and grids can significantly improve subgrade bearing capacity and stability, especially in soft or mixed ground[12].

Biaxial bamboo grids reinforced soil–rock combination subgrades better than uniaxial grids, with tensile strengths up to 630 MPa and elastic moduli higher than polymer geogrids[13]. The study also found that bamboo's strain-hardening pull-out and high interface friction make it excellent for subgrade stability. Bamboo grids boost clay beds' bearing capacity sixfold and contain settlement and deformation[14,15]. Bamboo piles and grids can support slopes and embankments, improving safety and minimising landslip risks. Synthetic geogrids are currently the industry standard based on their uniform mechanical properties and extended lifespan. However, some studies have shown that bamboo can be as good or superior in specific configurations[16].

Bamboo grids have 20 to 30 times the tensile and flexural strengths of commercial geogrids, although having less elongation[13]. The reinforced foundation's performance depends on the number of bamboo grid layers, their direction, and grid size.Bamboo reinforcement is susceptible to biological deterioration, especially when raw[15]. Long-term trials show that treated bamboo can last for years. However, bamboo species, age, and treatment vary, making standardisation difficult[17].

The literature shows that bamboo can replace synthetic geogrids and steel as subgrade reinforcement in low-volume highways without harming the environment. It succeeds with proper treatment, design, and quality control. Although more long-term field testing and standardisation are needed, a growing body of material supports bamboo's use in sustainable rural infrastructure construction. Table 1 summarises the most important bamboo reinforcement studies in subgrade applications, highlights their key findings and limitations, and compares them to the present work's innovative additions.

2.1 Proposed Methodology

This chapter explains the materials, sample preparation, and testing techniques applied to measure the performance of bamboo and synthetic geogrids for subgrade reinforcement. The main features involve material characterisation, laboratory tensile strength and durability tests, and model tests for measuring bearing capacity and settlement under loaded traffic conditions. The method guarantees an orderly comparison between the two reinforcing materials under specified conditions.

2.1.1 Data collection

The test phase of the research was conducted on the Delhi Technological University (DTU) campus. One of the important prerequisites of this research was to select a test location that could effectively represent the situation of an average unpaved road surface. A particular plot of land within a relatively

Table 1 — Summary of key studies on bamboo subgrade reinforcement.

Datasets	Methods	Key Findings	Limitations
Cohesion, friction angle, Load-settlement curves [33]	Direct shear tests	Bamboo grids improve shear strength in loess soils.	Limited to loess; no geosynthetic comparison.
Bearing capacity ratios, Stress-strain curves and modulus values[22]	Laboratory Bearing capacity tests, triaxial tests, FE modelling	Biaxial bamboo grids enhance bearing capacity in soil-rock mixes.	Lab-only; no field validation.
Load-deformation curves, Bearing capacity ratios[15]	Plate load tests, cyclic loading tests, and analytical modelling	Bamboo cells match geogrids in soft soils.	Static loads only; no cyclic testing.

low-traffic, less-used university campus region was chosen to achieve this.

2.1.2 Experimental setup and materials

This section describes the experimental setups and materials used in the program, including the subgrade soil, bamboo grids, geosynthetics, and base aggregates.

2.1.2.1 Subgrade

The subgrade soil used in the field tests was collected from the Delhi Technological University campus to ensure the utilisation of locally available material. Based on the unified soil classification system (USCS), the soil was classified as SM (sand with silty fines). Table 2 represents the soil properties used to characterise the subgrade soil, which has been tested in the laboratory. The specific gravity of the soil particles was established through the Pycnometer test and found to be 2.58.

2.1.2.2 Base course

The material used for the base course of the unpaved test section was simulated using stone aggregates classified as well-graded gravel (GW) according to the unified soil classification system (USCS). The particle size of the aggregate ranges from 4.75 to 12.5 mm. The specific gravity of the base course material is 2.65.

2.1.2.3 Bamboo grid

The experiment used *Dendrocalamus strictus* bamboo material with an 80-160 MPa tensile strength, constructed in a 50 cm × 50 cm grid with a square mesh pattern and an evenly spaced grid of approximately 2.5 inches in both longitudinal and transverse orientations. Bamboo strips about 4 mm thick were trimmed to lengths and widths and tied with galvanised wire at each intersection to stabilise and align grids. The grid was developed to distribute load throughout the subgrade and was dimensioned and spaced to compare with conventional geogrid reinforcement systems. Bamboo strips were dried in the sunshine before assembly to improve durability and performance in lab tests. Bamboo grid specifications are in Fig.1, and Table 3 summarises its key properties.

2.2 Materials testing and experimental methods

This section outlines the procedures and methodologies used for materials testing and experimental evaluation, detailing the characterisation of soil properties and the assessment of reinforcement performance under controlled conditions.

Table 2 — Soil parameters.

Parameter	Value	Interpretation
Effective grain size, D_{10} (mm)	0.084	
D_{30} (mm)	0.125	Soil is classified as silty sand (SM).
D_{60} (mm)	0.249	
Coefficient of curvature, C_c	2.96	
Coefficient of uniformity, C_u	0.747	
Optimum moisture content, OMC (%)	10.05	Moderate compaction
Maximum dry density, MDD (KN/m^3)	18.25	
Specific gravity, G_s	2.58	Inorganic soil
Liquid limit, LL (%)	17.87	Soil is non-plastic

Table 3 — Properties of the bamboo grid used.

Characteristics	Property	Description/Value
Physical Characteristics	Structure	Bi-axial bamboo grid
	Colour	Greenish Brown
	Aperture shape	Square
	Bamboo type/Species	Dendrocalamus strictus
Technical Characteristics	Aperture size(mm)	60 × 60
	Transversal rib width(mm)	4
	Longitudinal rib thickness(mm)	4
	Junction thickness(mm)	8

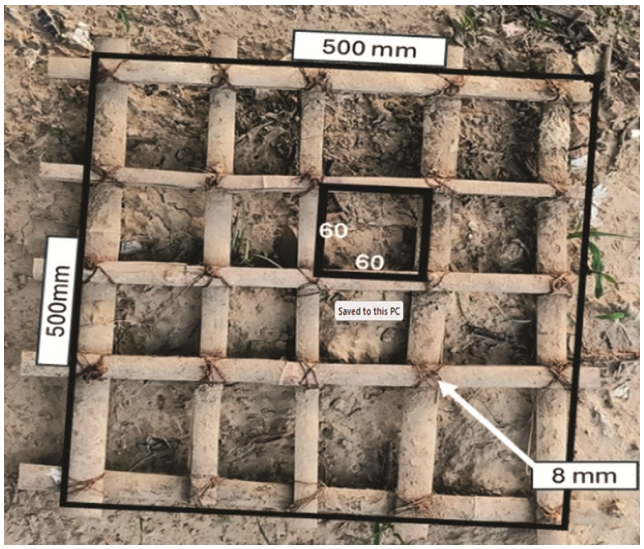


Fig.1 — Bamboo grid reinforcement placed on subgrade.

2.2.1 Laboratory investigation

Firstly, a thorough sieve analysis (IS 2720 Part 4) classified the virgin subgrade soil's texture for geotechnical description. The soil sample was mechanically agitated on a sieve shaker for

Table 4 — Laboratory test details.

Test	Method/Standard	Key Parameters	Equipment
Sieve Analysis	IS 2720 (Part 4)	Gravel, Sand, Fines distribution	Sieves (4.75 mm to 75 µm), Shaker
Modified Proctor	IS 2720 (Part 8)	OMC, MDD	1000 cm³ mould, 4.89 kg rammer
Specific Gravity	IS 2720 (Part 3)	Specific gravity (G)	Pycnometer, distilled water
Field Density	IS 2720 (Part 29)	Bulk density, Dry density	130 mm diameter core cutter
Atterberg Limits	IS 2720 (Part 5)	Liquid Limit (LL), Plastic Limit (PL)	Casagrande apparatus, grooving tool

15 minutes using 4.75 mm to 75 micron sieves. Every sieve's material was weighed to compute the cumulative percentage of gravel, sand, and fines for USCS classification. The modified proctor test (IS 2720 Part 8) was used to analyse compaction behaviour by compacting five layers of soil samples in a 1000 cm³ mould. Each layer received 25 blows from a 4.89 kg rammer from a height of 450 mm to determine the OMC-MDD relationship. A calibrated pycnometer bottle was filled with oven-dried soil and distilled water to calculate the ratio of water density to soil particle density to calculate soil solids' specific gravity (IS 2720 Part 3). Equation 2 calculates soil solids' specific gravity. In the core cutter technique (IS 2720 Part 29), a 130 mm cylindrical core cutter is driven into the earth to remove undisturbed cores, which are oven-dried to calculate bulk and dry densities. The Casagrande apparatus (IS 2720 Part 5) calculated Atterberg limits: liquid limit was the moisture content at which a typical groove in the soil paste closed in more than 25 blows, and plastic limit was the moisture content at which the soil thread snapped at 3 mm.Table 4 outlines the laboratory tests performed, their IS codes, key parameters, and equipment used.

2.2.2 Field investigation

The Dynamic Cone Penetration (DCP) gear applied during the present investigation came with ASTM D6951-03 requirements. The apparatus has a 60° cone with a 20 mm base, which is bonded onto a steel rod having a 16 mm diameter, as seen from the drawing provided by Fig. 2. It has an 8 kg weight that comes 575 mm to fall freely over it.

Under test conditions, the rod was held vertically to avoid variable penetration. A procedurally important consideration was holding the hammer raised only to the handle base while not lifting the cone to prevent measurement error when handling. Analysis excluded the first blow because, at initial penetration, the incomplete area of impression of the cone underestimates soil resistance. Penetration depth (in mm) was noted for every hammer blow that

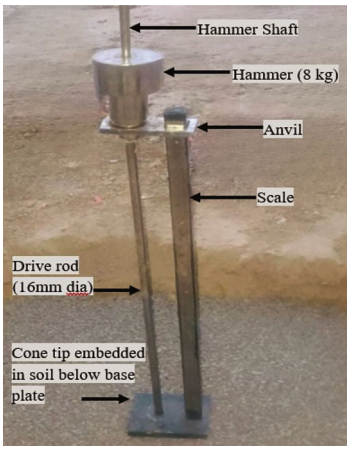


Fig. 2 — Direct cone penetration test apparatus.

followed. Dynamic Cone Penetration Index (DCPI), or the penetration depth per blow (mm/blow), was determined with two methods:

Incremental Method: The expression used for calculating DCPI using this method is given below as Equation (1):

$$DCPI = \frac{P_{(i+11)} - P_{(i)}}{N_{(i+1)} - N_{(i)}} \quad ...(1)$$

where, $P_{(i)}$ and $P_{(i+1)}$ represents penetration depths (mm) at blow counts $N_{(i)}$ and $N_{(i+1)}$,respectively.

Cumulative Gradient Method:A linear regression of cumulative penetration depth versus blow count was performed, with the slope of the best-fit line representing the DCPI.

Layer boundaries within the subgrade and base course were identified by abrupt changes in the slope of the penetration-depth vs. blow-count profile. For homogenised interpretation, an average DCPI value was derived using Equation 2:

$$DCPI_{avg.} = \frac{\sum_i^N DCPI}{N} \quad ...(2)$$

where, N denotes the total number of DCPI measurements within a specified penetration depth.

The diameter of the conical tip is slightly larger than the diameter of the rod to concentrate soil

resistance on the cone and minimise side friction. This approach allowed for accurate characterisation of in-situ strength and layer stratification, which is important for assessing subgrade performance under reinforcement.The Dynamic Cone Penetration Test (DCPT) was executed on both unreinforced and bamboo-reinforced subgrade sections to evaluate the improvement in in-situ strength.

The grid was installed at the base-subgrade interface for the bamboo-reinforced section and left undisturbed during testing. The test involved driving a 60-degree conical tip (20 mm base diameter) attached to a 16 mm steel rod into the soil using an 8 kg hammer dropped freely from a height of 575 mm. Penetration depth was recorded after each blow, excluding the initial blow due to incomplete cone imprinting. Vertical alignment of the rod was maintained to minimise friction and ensure accuracy. Data were analysed to calculate the Dynamic Cone Penetration Index (DCPI) as the total penetration depth (mm) ratio to total blows, directly comparing reinforced and unreinforced sections. The test provided empirical correlations between DCPI and engineering properties like California Bearing Ratio (CBR), quantifying the bamboo grid's effectiveness in enhancing subgrade stiffness and load-bearing capacity.

Three test sections were built for the field testing of bamboo grid reinforcement, each with a length of 500 mm, a width of 500 mm, and a total depth of 400 mm.The composition of each section had a 280 mm subgrade layer and a 120 mm base course layer, with the bamboo grid at the interface. The subgrade soil was prepared by distributing it in two 140-mm lifts and compacting it manually with an 8 kg rammer falling from 50 cm as per IS 2720. Before compacting, the soil was brought to 10.05% moisture to ensure layer density and stability. Bamboo grids (50 cm × 50 cm) with a biaxial orientation and 101.6 mm centre-to-centre distance were used in reinforced zones at the subgrade-base contact. Bamboo strips 20 mm wide and 8 mm thick were securely connected at junctions, and nearby grids overlapped by 15 cm to ensure structural integrity and reduce displacement in later construction. After grid laying, the base course aggregate was laid in a single 120 mm lift and rammed with the same rammer to 91% of the maximum dry density by laboratory compaction testing. Surface treatment of the aggregate layer's top concluded the segment. The test section building stages are shown in Fig. 3.

The blows and penetration depths were accurately recorded, with DCP tests continued to a maximum penetration of 545 mm or refusal. This thorough construction and testing procedure allowed for a valid comparison between the unreinforced and bamboo-reinforced test sections, which facilitated an exhaustive examination of the bamboo grid's subgrade and base course system performance.

3 Results and Discussion

This section presents and interprets the experimental findings, comparing the performance of unreinforced and reinforced subgrade sections and discussing the implications of bamboo and geosynthetic reinforcements on subgrade behaviour.

3.1 Effect of bamboo grid reinforcement: Experimental results

The experimental results from the unreinforced and bamboo-reinforced test sections reveal significant differences in subgrade performance under dynamic



Fig. 3 — Construction details of bamboo reinforced unpaved test section(a) Construction of test section with dimension

loading. For the unreinforced section, Dynamic Cone Penetration (DCP) tests recorded a penetration depth of 545 mm at 85 blows, with a Dynamic Cone Penetration Index (DCPI) of 6.4 mm/blow. In contrast, the bamboo-reinforced section achieved a reduced penetration depth of 448 mm at 200 blows, corresponding to a DCPI of 2.24 mm/blow. Table 5 presents the maximum penetration depths for each test section, along with the corresponding percentage improvement achieved by the bamboo-reinforced section compared to the unreinforced section.

This reduction underscores the bamboo grid's ability to enhance subgrade stiffness by confining soil particles and redistributing stresses laterally. The bamboo grid's biaxial configuration (50 cm × 50 cm, 4-inch spacing) facilitated effective interlocking with the granular base course and subgrade, limiting vertical deformation compared to an unreinforced subgrade section. Figure 4 shows the graphical comparison of both sections' penetration resistances.

3.2 Comparison of bamboo grid reinforcement with geosynthetic materials

The efficiency of bamboo grid reinforcement was evaluated compared to geogrid and geotextile systems through field Dynamic Cone Penetration Tests (DCPT), with findings presented in Table 6.

Table 5 — Maximum penetration depths and percentage improvement for each test section.

Subgrade condition	Maximum number of blows	Maximum penetration depth	DCPI (mm/blow)	Percentage improvement (%)
Unreinforced	85	545	6.4	--
Bamboo-Reinforced	200	448	2.24	65

The unreinforced section demonstrated the least effective performance, necessitating only 85 blows to achieve a penetration depth of 545 mm, resulting in the highest DCPI of 6.4 mm/blow. The geogrid-reinforced section exhibited enhanced resistance, necessitating 153 blows to reach an equivalent penetration depth of 545 mm, corresponding to a 31.56% reduction in DCPI (4.38 mm/blow). This demonstrates the geogrid's efficacy in load distribution and soil interlocking, especially in high-stress scenarios. The geotextile-reinforced section demonstrated superior performance compared to both geogrid and bamboo, attaining the lowest DCPI of 2.04 mm/blow, which represents a 68.13% improvement over the unreinforced condition, with a penetration depth of 350 mm at 153 blows. This highlights the geotextile's remarkable capacity to contain soil particles and laterally redistribute stresses. The bamboo-reinforced section attained a penetration depth of 448 mm after 200 blows, resulting in a DCPI of 2.24 mm/blow, representing a 65% enhancement compared to the unreinforced variant. Bamboo's performance was marginally inferior to that of geotextiles, yet it demonstrated comparable stress distribution to geogrid and significantly surpassed the unreinforced scenario.

To further illustrate the relative effectiveness of each reinforcement method, a graphical comparison of the maximum penetration depth and DCPI values for unreinforced, bamboo-reinforced, geogrid-reinforced, and geotextile-reinforced sections is presented below. Figure 5, a visual representation, highlights the improvements achieved with each type of reinforcement and facilitates an easy comparison of their performance in subgrade stabilisation.

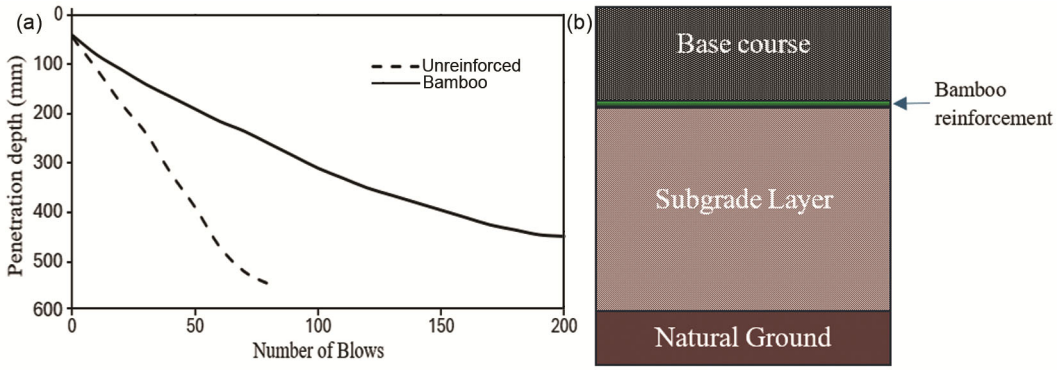


Fig. 4 — (a)Penetration resistances, Bamboo reinforced vs. Unreinforced section and (b) Schematic cross-section of bamboo-reinforced pavement subgrade.

Table 6 — Performance comparison of subgrade reinforcement methods.

Subgrade Reinforcement	Maximum No. of blows	Maximum Penetration depth	DCPI (mm/blow)	Percentage decrease in DCPI (%)
Geogrid [28]	153	545	4.38	31.56
Geotextile [28]	153	350	2.04	68.125
Bamboo *	200	448	2.24	65
Unreinforced *	85	545	6.4	-

*Present study

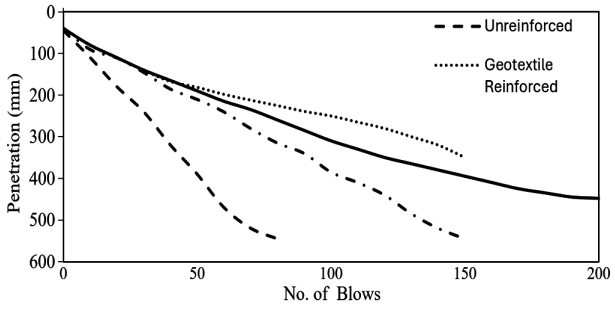


Fig. 5 — Comparison of penetration depths of unreinforced, bamboo, geogrid, and geotextile reinforced subgrade sections.

4 Conclusion

The tested subgrade was classified as SM (poorly graded sand with silt), a non-cohesive, low-plasticity soil. Bamboo grids effectively confined these particles, enhancing strength and reducing deformation. The key conclusions drawn from this study are summarised below:

a Bamboo grid reinforcement significantly improved subgrade strength compared to unreinforced soil. The DCPI dropped from (6.4 mm/blow)for unreinforced to (2.24 mm/blow)for bamboo, a 65% reduction. The bamboo-reinforced section also required more than twice the number of blows to reach a similar penetration depth, indicating greater resistance and stiffness.

b Compared to geosynthetics, bamboo performed nearly as well as geotextile (DCPI: 2.04 mm/blow, 92% of the improvement) and outperformed geogrid (DCPI: 4.38 mm/blow, 48.9% greater reduction in DCPI). This shows bamboo grids can be a practical alternative to synthetic materials in many scenarios.

c Bamboo grid reinforcement offers a practical, cost-effective, and sustainable method for enhancing subgrade strength, delivering performance close to geotextiles and better than geogrids in silty sand soils. Its environmental benefits, local availability, and proven durability make bamboo an excellent choice for rural and low-volume road applications.

Recommendations for future work

a Investigate bamboo grids combined with geotextiles or lime stabilisation to optimise load distribution and interfacial shear strength in diverse soil types (e.g., silty sand, loess).

b Assess bamboo grid performance under cyclic wet-dry conditions, UV exposure, and seismic loads to validate lifespan (15–20 years) and refine treatment methods.

c Develop design guidelines for grid spacing, aperture size, and installation protocols to enable widespread adoption in low-volume roads and embankments.

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