A Comparative Analysis of Reinforced Flexible Pavement Performance over Various Subgrades

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Abstract - The performance of flexible pavements depends greatly on the strength and behavior of the underlying subgrade. Weak subgrades lead to early distress, higher maintenance costs, and increased life-cycle expenses. This study compares the behaviour of pavements constructed on clay, silt, sand, and laterite subgrades under reinforced and unreinforced conditions, with the aim of assessing how reinforcement improves strength, deformation characteristics, and overall performance. Laboratory investigations included index properties, Proctor compaction, CBR, UCS, settlement measurements, and rutting tests. Each soil was evaluated first in its natural state and then with geogrids, geotextiles, and natural fibers, chosen for their availability and cost-effectiveness. Reinforcement significantly improved engineering properties across all soils. CBR values increased notably—over 100% in clay—while UCS values nearly doubled, especially in fine-grained soils. Reinforced samples also exhibited lower settlements and reduced rut depths, resulting from improved stress distribution and restricted lateral soil movement. Among the materials tested, geogrids provided the highest improvement, followed by geotextiles and natural fibers. The study also indicates the potential to reduce pavement thickness without compromising performance, lowering material and construction costs. Overall, the findings confirm that soil reinforcement enhances pavement durability, promotes sustainable design, and offers practical benefits for regions with weak subgrade conditions.

***Key Words*:** clay, silt, sand, laterite, soil reinforcement, and geogrid.

1. INTRODUCTION

Road transport is the most widely used mode of transportation in India due to its flexibility, accessibility, and cost-effectiveness. With over 65% of goods and 80% of passengers moving by road, durable pavement infrastructure is essential for economic development and connectivity. Among pavement types, flexible pavements are preferred because they are economical, easier to construct, and simpler to repair compared to rigid pavements. However, their long-term performance depends heavily on the strength of the subgrade soil that supports the pavement layers.

A flexible pavement consists of a bituminous surface course, a load-distributing base and sub-base, and a compacted soil subgrade. The subgrade acts as the foundation; weak subgrades can lead to excessive deflections, rutting, fatigue cracking, potholes, and differential settlement. Soil properties vary widely across India—clays swell and shrink, silts lose strength when wet, sands lack cohesion, and laterites weaken during heavy rainfall. Such variability often results in premature pavement failure if untreated.

Reinforcing the subgrade has emerged as a reliable solution to overcome these issues. Reinforcement materials such as geogrids, geotextiles, natural fibers (jute, coir, bamboo), and chemical stabilizers (lime, cement, fly ash) enhance soil strength, reduce deformation, and improve overall pavement performance. Geogrids provide interlocking and load distribution, while geotextiles offer separation and filtration; natural fibers present a cost-effective and eco-friendly alternative. Chemical stabilizers modify soil properties, making weak soils suitable for road construction.

Reinforcement leads to higher load-carrying capacity, reduced rutting, longer fatigue life, and extended pavement service life. It also enables a reduction in pavement layer thickness, lowering construction costs. In India, where subgrade conditions vary significantly, reinforcement is particularly valuable, especially in rural and economically sensitive regions.

Overall, reinforced flexible pavements provide a durable, economical, and sustainable solution for improving road performance over weak subgrades.

2. PROBLEM STATEMENT, OBJECTIVES, SCOPE, AND OUTCOMES

2.1 Problem Statement

India’s road network carries the majority of passenger and freight traffic but rising vehicle numbers and repeated overloading have accelerated the deterioration of flexible pavements. Premature failures—such as rutting, cracking, potholes, and uneven settlement—are common, particularly where pavements rest on weak subgrades, including clay, silt, laterite, or expansive soils. These soils exhibit low strength, high moisture sensitivity, and large deformations under traffic loads. Conventional pavement designs often assume uniform subgrades; however, Indian soils vary widely, leading to pavements underperforming and resulting in high maintenance costs. Therefore, cost-effective methods are needed to improve pavement performance on weak subgrades.

2.2 Objectives of the Study

The study aims to evaluate the performance of reinforced flexible pavements on different subgrades. The specific objectives are:

To examine the engineering properties of clay, silt, sand, and laterite soils.

To assess the effectiveness of geogrids, geotextiles, and natural fibers in improving subgrade strength.

To compare reinforced and unreinforced pavements in terms of rutting, fatigue life, and load capacity.

To determine whether reinforcement reduces base/sub-base thickness.

To perform a cost–benefit analysis of reinforced pavements.

To propose design guidelines suitable for Indian conditions.

2.3 Scope of the Study

The study encompasses laboratory characterization of soils, the use of geosynthetics and natural fibers as reinforcement, CBR and strength testing, the preparation of reinforced and unreinforced model pavement sections, analytical evaluation using standard design methods, and a cost analysis. Large-scale field trials are excluded.

2.4 Expected Outcomes

Expected outcomes include improved CBR and strength of weak soils, reduced rutting and cracking, longer pavement life, reduced layer thickness and cost, validation of natural fibers as sustainable reinforcement, and recommendations for reinforcement strategies and design guidelines for Indian road projects.

3. LITERATURE REVIEW

Flexible pavements are widely used due to their low cost and ease of construction; however, their performance depends heavily on the strength of the subgrade. Weak soils such as clays, silts, and laterites often lead to premature failures. Studies by Seed and Chan (1961), Sridharan and Nagaraj (2005), and Sivapullaiah et al. (2007) have demonstrated that these soils lose strength with increasing moisture and undergo significant deformations, rendering them unsuitable for use without improvement.

Geosynthetics are one of the most effective methods of reinforcement. Research by Giroud and Han (2004), Cancelli and Montanelli (1999), and Sitharam and Sireesh (2005) demonstrated that geogrids and geotextiles reduce rutting, improve load distribution, and allow thinner pavement layers. However, their cost limits use in rural roads.

Natural fibers, such as coir, jute, and bamboo, offer low-cost, sustainable alternatives, while chemical stabilizers, including lime, cement, and fly ash, effectively improve expansive soils. Existing studies often focus on single soil types. A major gap remains in comparing reinforced pavements across multiple subgrades under Indian conditions—a gap this study aims to address.

4. MATERIALS AND METHODOLOGY

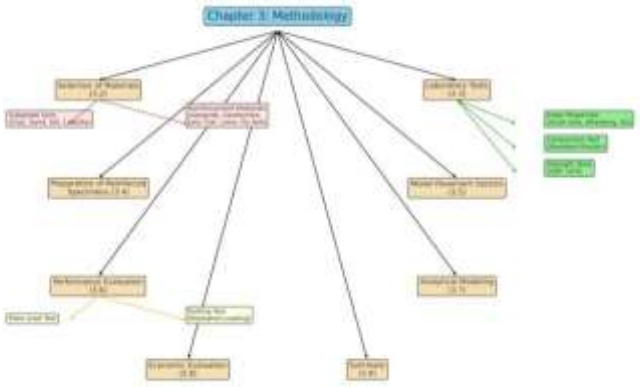

Figure 1. Flow chart of the methodology adopted

This chapter outlines the methodology adopted to evaluate the performance of flexible pavements reinforced with different materials over various subgrade soils. The study involved selecting representative subgrades—clay, sand, silt, and laterite—and choosing suitable reinforcement materials, including geogrids, geotextiles, jute, coir, lime, and fly ash. Each soil was classified through index property tests, followed by compaction, CBR, and UCS tests to establish baseline strength. Reinforced specimens were prepared by placing geosynthetics or fibers at predetermined depths, while chemical stabilizers were mixed with clay to assess combined improvement. Small-scale model pavement sections were constructed with compacted layers to simulate field conditions. Performance was evaluated using plate load and rutting tests under repeated loading. Analytical modelling using IITPAVE estimated critical strains and pavement life. A cost analysis was conducted to compare reinforced and conventional designs and assess their economic feasibility. This structured methodology ensured a reliable, comparable, and comprehensive assessment of pavement behaviour.

5. RESULTS AND DISCUSSION

Table -1: Index Properties of Soils

Soil Type	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	Specific Gravity	IS Classification
Clay	65	28	37	2.68	CH (Expansive Clay)
Sand	NP	NP	NP	2.65	SP (Poorly Graded Sand)
Silt	45	25	20	2.67	ML (Low Plastic Silt)
Laterite	40	23	17	2.70	SC (Silty Clay, Lateritic)

These values show that clay is highly plastic, sand is non-plastic, silt is moderately plastic, and laterite has medium plasticity.

Figure 2. Compaction test results using the standard proctor method

The compaction results show clear differences in OMC and MDD among the soils. Clay exhibits the highest OMC (18%) due to its high plasticity, while silt and laterite show moderate moisture requirements. Sand has the lowest OMC (11%) because of its coarse, non-plastic nature. In terms of MDD, sand achieves the highest density (1.92 g/cc) due to efficient particle packing, followed by laterite (1.82 g/cc). Silt (1.75 g/cm³) and clay (1.68 g/cm³) exhibit lower densities due to their fine texture and higher water retention capacities. Overall, sand compacts most efficiently, whereas clay requires more moisture and yields lower density.

Figure 3. CBR Comparison (Reinforced vs Unreinforced)

Reinforcement significantly improves CBR across all soil types, with clay showing the highest gain (106%) due to its naturally low strength. Silt also responds well, exhibiting a 67% increase in bearing capacity. Laterite shows a 53% improvement, indicating good compatibility with reinforcement. Sand, though already strong with the highest unreinforced CBR (8.5%), still records a 38% increase, enhancing overall stability. These results demonstrate that reinforcement is effective for both weak and moderately strong soils, with the greatest benefits observed in softer subgrades. Overall, reinforced soils exhibit markedly improved load-bearing capacity, making them more suitable for pavement and foundation applications.

Table - 2: UCS Values (kN/m²)

Soil Type	UCS Unreinforced	UCS Reinforced	% Improvement
Clay	110	210	91%
Sand	150	220	47%
Silt	130	195	50%
Laterite	160	250	56%

The UCS results indicate a significant increase in strength across all soils following reinforcement. Clay exhibits the highest improvement, rising from 110 to 210 kN/m² (91%), reflecting its strong response due to weak natural strength. Sand increases from 150 to 220 kN/m² (47%), indicating enhanced interlocking despite already high strength. Silt improves from 130 to 195 kN/m² (50%), showing better stability of its fine structure. Laterite increases from 160 to 250 kN/m² (56%), confirming its good compatibility with reinforcement. Overall, reinforcement significantly enhances compressive strength in all soils, with the greatest benefit in clay and substantial gains in sand, silt, and laterite.

Table - 3: Settlement at 40 kN Load

Soil Type	Settlement (mm) Unreinforced	Settlement (mm) Reinforced	Reduction (%)
Clay	12.0	6.0	50%
Sand	9.5	6.8	28%
Silt	11.2	7.2	36%
Laterite	8.0	6.2	22%

The settlement results at 40 kN show that reinforcement effectively reduces deformation in all soils. Clay exhibits the highest reduction, decreasing from 12.0 mm to 6.0 mm (50%), due to improved load distribution in its weak, plastic structure. Silt exhibits a 36% reduction (from 11.2 mm to 7.2 mm), indicating improved stability of its fine-grained matrix. Sand shows a smaller reduction of 28% (from 9.5 mm to 6.8 mm), as it is already dense and stable. Laterite records the least reduction (22%), dropping from 8.0 mm to 6.2 mm. Overall, reinforcement enhances deformation resistance, with the most significant benefits observed in soils with weaker properties.

Table – 4: Rut Depth after 5000 Load Cycles

Soil Type	Rut Depth (mm) Unreinforced	Rut Depth (mm) Reinforced	% Reduction
Clay	25	12	52%
Sand	18	10	44%
Silt	22	13	41%
Laterite	15	11	27%

The rutting test results show that reinforcement greatly reduces permanent deformation under repeated loading for all soils. Clay exhibits the highest improvement, with a decrease in rut depth from 25 mm to 12 mm (52%), reflecting its enhanced stability. Sand shows a 44% reduction (18 mm to 10 mm), indicating better confinement of its granular structure. Silt records a 40% reduction (22 mm to 13 mm), demonstrating improved resistance to traffic-induced deformation. Laterite shows the smallest reduction, at 27% (from 15 mm to 11 mm), but still benefits noticeably. Overall, reinforcement enhances rut resistance and improves long-term pavement performance, particularly for soils with weaker properties.

Table - 5: Reinforced vs Unreinforced Soil Performance

Soil Type	CBR (UR)	CBR (R)	UCS (UR)	UCS (R)	Settlement (UR)	Settlement (R)
Clay	3.0	6.2	110	210	12.0	6.0
Sand	8.5	11.8	150	220	9.5	6.8
Silt	4.2	7.0	130	195	11.2	7.2
Laterite	6.0	9.2	160	250	8.0	6.2

The results clearly demonstrate that reinforcement significantly enhances the performance of flexible pavements on weak subgrades. CBR and UCS values increased substantially, nearly doubling in clay and improving by 40–60% in other soils. Reinforced sections showed lower settlements and higher stiffness, while rutting tests confirmed better resistance to permanent deformation under repeated loads. Overall, clay benefited the most, followed by silt, laterite, and sand. Reinforcement consistently improves strength, reduces deformation, and extends pavement life.

6. CONCLUSIONS

1. Subgrade Variability Affects Pavement Performance

Index and strength tests showed clear differences in soil behavior. Clay exhibited swelling and shrinkage, silt was moisture-sensitive, sand lacked cohesion, and laterite weakened when soaked. These variations underscore the importance of considering subgrade conditions in pavement design.

2. Significant Improvement in CBR

Reinforcement substantially increased CBR values. Clay showed over 100% improvement, while silt, laterite, and sand improved by 67%, 53%, and 38%. Higher CBR values indicate reduced pavement thickness requirements.

3. Increased UCS Strength

UCS values nearly doubled in reinforced clays, while sand, silt, and laterite showed an improvement of 40–60%. Reinforcement enhanced tensile resistance and compressive performance.

4. Reduced Settlement

Reinforced pavement sections experienced significantly lower settlement; the clay layer was reduced from 12 mm to 6 mm under a 40 kN load, indicating improved stiffness and load distribution.

5. Improved Rutting Resistance

Rutting depths significantly decreased, with clay reducing from 25 mm to 12 mm. All soils exhibited better resistance under repeated loads.

6. Analytical and Economic Benefits

IITPAVE analysis confirmed lower critical strains and longer pavement life. Despite a slightly higher initial cost, reinforcement reduced layer thickness and maintenance. Natural fibers offered additional sustainability and cost advantages.

7. FUTURE SCOPE OF THE STUDY

1. Field Trials and Long-Term Monitoring

This study was limited to laboratory and analytical evaluations. Future work should include full-scale field trials to validate reinforcement performance under real-world traffic conditions, climatic variations, and long-term aging.

2. Exploration of Advanced Materials

Beyond geogrids, geotextiles, jute, and coir, future studies can test geocells, hybrid reinforcements, and nano-modified polymers for enhanced strength and durability.

3. Combined Reinforcement–Stabilization Methods

Research can explore the integration of reinforcement with chemical stabilizers, such as lime, cement, or fly ash, particularly for expansive or highly problematic soils.

4. Performance in Extreme Climates

Future studies should examine reinforced pavements under conditions of heavy rainfall, flooding, extreme heat, and desert environments to understand climate-dependent behavior.

5. Life Cycle Cost Analysis

A comprehensive life cycle assessment that encompasses construction, maintenance, and user costs will help evaluate the long-term economic benefits.

6. Environmental Impact Assessment

Quantifying carbon footprint, recyclability, and biodegradability of natural fibers will support sustainable pavement practices.

7. Advanced Simulation Tools

Finite element software, such as PLAXIS or ANSYS, can be used for 3D modeling and the accurate prediction of reinforced pavement behavior.

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