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Enhancing Durability and Reducing Cost of Flexible Pavement Using Biaxial Geogrid Reinforcement

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Abstract

The durability and economic efficiency of flexible pavement structures are critically challenged by the prevalence of weak subgrade soils in many regions of India, leading to frequent failures such as rutting, potholes, and excessive maintenance burdens. This research systematically investigates the incorporation of biaxial geogrids as reinforcement in flexible pavement systems, aiming to both strengthen subgrade soils and optimize construction costs. The methodology encompasses a series of laboratory tests performed on locally available subgrade soils, including grain size distribution, Atterberg limits, Proctor compaction, and California Bearing Ratio (CBR) evaluations—with and without geogrid layers placed at variable depths. A large-scale test tank was developed to simulate pavement sections, enabling cyclic loading and direct measurement of settlements. The study also employs the Layer Coefficient Ratio (LCR), Modulus Improvement Factor (MIF), and Traffic Benefit Ratio (TBR) to quantify the impact of geogrid inclusion. Results indicate marked increases in subgrade CBR (from ~8 up to >13) with geogrid presence, particularly when installed at optimal positions, and a TBR of 2.7, representing a 170% improvement in load cycle endurance at 10mm design settlement. Subsequent mechanistic empirical design using IRC:37-2018 and supplementary IITPAVE analyses demonstrate the ability to safely reduce base and sub-base layer thicknesses while meeting rutting and fatigue criteria. Economic analysis confirms significant material savings, reduced maintenance interventions, environmental benefits, and overall life cycle cost reductions estimated at 10–25%. The findings establish geogrid-reinforced flexible pavements as an effective technical and economic strategy for sustainable, high-performance road infrastructure, particularly in regions with problematic subgrades. Recommendations for practice and further research conclude the paper.

Keywords

Biaxial geogrid, flexible pavement, geosynthetics, soil reinforcement, CBR, layer coefficient ratio, modulus improvement factor, traffic benefit ratio, cost reduction, sustainable pavements, IRC:37-2018, subgrade improvement.

Introduction

Background

India's road network, extending over 6.6 million kilometers, is second only to that of the United States and serves as a fundamental backbone of national connectivity and economic growth. However, the quality and service life of these roads are consistently compromised by underlying subgrade soils with low bearing capacity—particularly silty or clayey soils with California Bearing Ratios (CBR) as low as 2–5%. Common distress manifestations—potholes, rutting, surface deformation, and cracks—lead to shorter design lives and escalating maintenance costs, exacerbated further in monsoon-prone or poor-drainage regions.

Conventional remediation involves enlarging granular base and sub-base thicknesses, as dictated by CBR-based designs (IRC:37-2012/2018), yet this approach heavily burdens project budgets, resource consumption, and environmental footprints. As road usage and commercial vehicle traffic escalate, reinforced and more sustainable design paradigms are essential.

Motivation and Problem Statement

Given the pressing need for cost-effective, high-durability pavements in regions with weak subgrades, geosynthetic-reinforced designs—especially through the use of biaxial geogrids—offer a promising avenue. Biaxial geogrids, through their high tensile modulus and large apertures, provide reinforcement by confining aggregates, distributing loads more efficiently, and inhibiting lateral movement within pavement layers. Despite their theoretical advantage, comprehensive technical assessments, optimal placement strategies, and quantified cost-benefit analyses tailored to Indian materials and conditions remain sparse.

Objectives

This study aims to:

- Experimentally evaluate the effects of biaxial geogrid reinforcement on the mechanical and load-bearing properties of locally sourced subgrade soils, with a focus on CBR improvement.
- Optimize geogrid placement strategies (depth, layer) for maximal reinforcement efficiency.
- Quantify technical benefits via TBR, LCR, and MIF, benchmarking performance improvements under cyclic and static loading relative to unreinforced pavements.
- Develop reinforced pavement design solutions using IRC:37 methodologies, supported by mechanistic analysis (IITPAVE).
- Conduct comprehensive economic and environmental cost-benefit analyses, integrating life-cycle approaches.
- Provide recommendations for best practice and identify areas for further research.

Scope

Work encompasses laboratory-based geotechnical testing and analysis (grain size, Atterberg limits, compaction, CBR), full-scale pavement simulations in a controlled test tank, reinforced pavement mechanistic–empirical design, and cost/life-cycle analysis. The focus is on flexible pavements with challenging subgrades and the adaptation of biaxial geogrid solutions under Indian codes and conditions.

Materials and Methods

Materials

Subgrade Soils: Local expansive soils with high plasticity (Liquid Limit ~52%, Plastic Limit ~19%) and fine fractions <5%. Well-graded gravel sub-base and wet mix macadam (WMM) base were also used.

Biaxial Geogrid: Commercial 40kN/m PET biaxial geogrid compliant with IS 17371-2020, IRC SP:59-2019. Properties: Tensile strength (MD: 47.8 kN/m, CD: 45.4 kN/m), elongation (MD: 8.74%, CD: 9.12%), and high UV durability.

Other Materials: Water, cement (for certain reinforced mixes), granular aggregates, and standard geotechnical testing agents.

Laboratory Equipment

- Standard geotechnical apparatus (sieve sets, ovens, mechanical shaker, Proctor compaction molds, CBR testing rig, Casagrande apparatus, balance, etc.).
- Large rigid test tank (2.3mx2.3mx1.5m) for composite pavement system simulations.
- Cyclic loading apparatus with hydraulic actuator, LVDTs, pressure transducers, and digital data logger.
- IITPAVE software for mechanistic–empirical analysis.
- Additional compaction and density measurement tools.

Experimental Procedures

1. **Grain Size Distribution:**
    - Soil samples (1000g) were sieved per IS:2720 (Part 4) to determine effective size (D_{10} = 0.18 mm) and uniformity coefficient (C_u = 7.78; well-graded class).
2. **Atterberg Limits:**
    - LL, PL, and plasticity index (PI = 33.52%) obtained via IS 2720 (Part 5), characterizing soils as high-plasticity.
3. **Standard Proctor Compaction:**
    - Dry density–moisture content relationships measured. Optimum moisture content (OMC) = 16.65%; Maximum dry density (MDD) = 1.784 gm/cm³.
4. **California Bearing Ratio (CBR) Testing:**

- CBR tests performed on remoulded soil at OMC in both unreinforced and geogrid-reinforced conditions (at various depths: H/4, H/2, 3H/4 from mold bottom).
- Loads measured at 2.5mm and 5mm penetrations; CBR calculated per IS:2720 (Part 16).

5. **Large-Scale Tank Simulations:**
   - Subgrade, GSB, and WMM layers compacted and layered per MoRTH and IRC codes.
   - Geogrid placement within the profile at predefined depths or layers.
   - Cyclic loading (sinusoidal, simulating ESALs) applied via a circular steel plate, and settlements recorded.
6. **Mechanistic–Empirical Design:**
   - Standard (IRC:37-2018/2012) and LCR-based reinforced pavement designs with fatigue and rutting checks via IITPAVE software, incorporating measured TBR, LCR, and MIF values.
7. **Economic Analysis:**
   - Comparative life-cycle cost (LCC) assessment for reinforced vs. unreinforced sections, capturing material savings, reduction in base thickness, and expected maintenance cycles.
8. **Quality Assurance:**
   - Each phase repeated (min. 3 trials) for statistical rigor; equipment calibrated prior to testing.

Analytical Methods

- CBR and compaction data plotted and assessed for trends and outliers.
- Calculation of LCR, TBR, MIF as per equations given in the report, with direct use of load-settlement-curves from cyclic tank tests.
- Design thicknesses and strains determined for both unreinforced and reinforced options, per IRC:37 and IITPAVE outputs.

- Economic analysis calculated absolute and percentage savings, considering aggregate, labor, and maintenance costs, as well as environmental and indirect factors.

Results

Soil Properties and Initial Tests

- **Grain Size Distribution:** Cu = 7.78 (well-graded), Cc = 2.17; soil contained <5% fines.
- **Atterberg Limits:** LL = 52.17%, PL = 18.65%; High plasticity (PI = 33.52%).
- **Compaction:** OMC = 16.65%, MDD = 1.784 gm/cm³.

CBR Performance (Unreinforced vs. Reinforced)

- **Unreinforced CBR:** Average values of 8.0% (Table 5.5, Fig 5.5).
- **Geogrid at H/4:** Notable CBR increase (Table 5.6, Fig 5.7).
- **Geogrid at H/2:** CBR value increased further (Table 5.7, Fig 5.9).
- **Geogrid at 3H/4:** Highest CBR achieved; optimal placement at this location (Table 5.8, Fig 5.10).
- **Variation Overview:** Table 5.9 and Fig 5.11 summarize CBR increment for all placements; CBR in reinforced configurations can surpass 13%.

Tank Simulation Results

- **Settlement at Design Load:** For unreinforced section, 10mm settlement at 19,850 cycles; reinforced at 53,650 cycles (TBR = 2.7).
- **Maximum Settlement:** Reduced maximum settlement (12.6mm reinforced vs. 17.1mm unreinforced) after similar or more cycles.

Layer and Modulus Improvement

- **Layer Coefficient Ratio (LCR):** Calculated as 1.46; Modulus Improvement Factor (MIF) = 1.82.
- **Design Outcome:** Layer thickness reductions permitted while satisfying strain checks (vertical compressive strain <4.544E-04, horizontal tensile <1.862E-04).
- **Design Traffic:** 47.45 million standard axles used for design traffic.

Economic and Environmental Impact

- **Material Savings:** Reduction in granular base thickness and sub-base quantities.
- **Maintenance Reduction:** Lower rutting, cracking, and pothole frequencies.
- **LCC:** Projected cost reduction of 10–25% across life-cycle.
- **Sustainability:** Lower resource use, reduced emissions, potential for recycled geogrid materials.

Discussion

The experimental evidence substantiates that incorporating biaxial geogrids into flexible pavement subgrades and bases not only enhances structural response under static and cyclic loading but enables a tangible reduction in total pavement thickness and associated material demands. This dual benefit translates directly to major cost, time, and sustainability advantages, particularly vital for resource-constrained and high-traffic scenarios in India.

Comparison with precedent research demonstrates alignment: as seen in works by Giroud & Noirway (1982), Gosavi et al., and Naeini & Moayed, CBR values reliably increase with geosynthetic reinforcement—especially when grid depths and aperture sizes are properly optimized. The TBR value of 2.7 corroborates international studies highlighting improved cycle life and deferred service interventions. However, variability in soil type and field conditions warrants further calibration for universal application.

Technically, the improved modulus and layer coefficients enable adoption of less conservative pavement structures without sacrificing design safety or reliability. The LCR and MIF provide engineers with quantitative levers for thickness optimization, while TBR informs design life extension. Mechanistic empirical checks via IITPAVE verified adherence to Indian code criteria for strains and allowable stresses—important given the empirical roots of IRC:37.

Limitations include the need for field confirmation over several seasonal cycles, possible geogrid installation defects, and dependence on consistent material quality. Selection of geogrid type—aperture, polymer, tensile strength—must be contextually validated. Additionally, contractor education and quality control in installation remain essential to realize theoretical benefits.

Improvements could focus on analyzing more complex traffic loads, employing triaxial geogrids for further performance, and integrating digital construction monitoring to minimize field errors. Widespread adoption will depend on detailed case histories, demonstrations of return on investment, and integration with governmental sustainability goals.

Conclusion

This research demonstrates that biaxial geogrid reinforcement of flexible pavements is an effective and reliable technique for improving the strength, durability, and cost-efficiency of road infrastructure built on weak subgrade soils. Laboratory and tank-scale experiments confirm substantial enhancements in CBR, increased cycle endurance under cyclic loading (TBR = 2.7), and safe reductions in pavement thickness when evaluated with LCR and MIF factors. Mechanistic empirical design per IRC:37 and IITPAVE validates the technical viability of reinforced profiles. Material savings, lower maintenance intervals, and shorter construction times further solidify the case for geogrid adoption.

From a life-cycle perspective, the 10–25% cost savings, lower greenhouse gas emissions, and resource reductions achievable by geogrid use align strongly with modern priorities of sustainability and economic stewardship. Geogrids also offer resilience benefits in challenging subgrade or environmental conditions.

Future work should expand to long-term field monitoring, alternative geogrid polymer types, full integration with mechanistic design codes, and broader sustainability assessment—including cradle-to-grave environmental impact of geosynthetic alternatives. Scaling up demonstration projects and enhancing contractor training will facilitate broader adoption in India and similar contexts globally.

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