Optimizing Flexible Pavement Durability and Performance through Advanced Geo-grid Reinforcement Technique

Mayank Saxena[1], Vivek Kumar[2]

[1]*Research Scholar, Department of Civil Engineering, Mewar University, Chittorgarh, Rajasthan*
[2]*Vivek Kumar, Assistant Professor, Department of Civil Engineering, Mewar University, Chittorgarh, Rajasthan*

***

Abstract - *Geogrid reinforcement is increasingly used to improve the durability and structural efficiency of flexible pavements subjected to weak subgrades, repeated traffic loading, and environmental distress. This manuscript reorganizes the submitted M.Tech. thesis into an SCI-style research paper and evaluates the influence of biaxial and triaxial geogrids on laboratory and field performance of flexible pavement systems. The research combines California Bearing Ratio (CBR), wheel-tracking, repeated-load triaxial, flexural fatigue, and plate-load testing with six months of field monitoring and life-cycle cost analysis. Geogrid reinforcement increased soaked CBR from 4.7% to 7.6%, reduced laboratory rut depth from 17.5 mm to 8.65 mm, improved resilient modulus from 144 MPa to 239 MPa, and increased fatigue life from 18,000 to 32,650 cycles. In field sections, average rut depth decreased from 15.2 mm to 7.3 mm and average FWD deflection decreased from 1.99 mm to 1.23 mm. Economic evaluation over a 20-year period showed a lower net present value for the reinforced pavement (₹76.1 lakh) than for the control section (₹94 lakh), with a benefit-cost ratio of 1.66. The results demonstrate that geogrid reinforcement improves aggregate confinement, stress distribution, and rutting resistance while providing long-term cost advantages. Among the evaluated options, triaxial reinforcement and shallower placement within the loaded zone produced the strongest response.*

***Key Words*: flexible pavement; geogrid reinforcement; rutting resistance; resilient modulus; fatigue life; life-cycle cost analysis.**

1. INTRODUCTION

Flexible pavements are widely adopted because of their comparatively low initial cost, rapid construction, and maintainability. Their long-term performance depends on efficient stress transfer across the asphalt layer, base, subbase, and subgrade. Under modern traffic demand, premature rutting, fatigue cracking, and moisture-related deterioration have become common, especially where granular layers lose confinement or the supporting soil is weak.

Geogrids are polymeric reinforcement products designed with open apertures that mechanically interlock with aggregates. When placed at critical interfaces, they reduce lateral aggregate movement, increase layer stiffness, and spread wheel loads over a wider area. The thesis on which this manuscript is based investigated whether these benefits translate into measurable gains in pavement capacity, field durability, and economic efficiency under Indian conditions.

The study had four principal aims: (i) quantify the mechanical benefits of geogrid reinforcement in flexible pavement layers; (ii) compare rutting, fatigue, modulus, and deflection behavior between reinforced and unreinforced sections; (iii) identify favorable geogrid type and placement depth; and (iv) evaluate long-term cost-effectiveness using life-cycle costing.

2. Literature Survey & Survey Gap

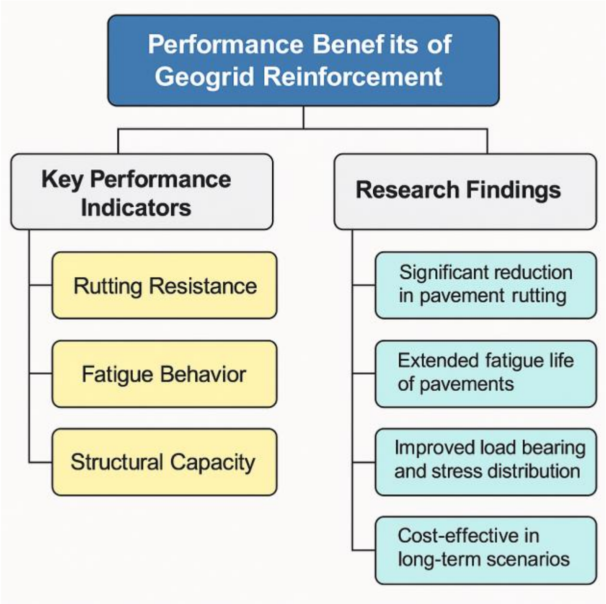

Fig -1: Conceptual summary of the performance benefits reported for geogrid reinforcement

Table -1: Key findings and research gaps summarized from the literature review

S. N.	Author (s) & Year	Title	Methodology	Key Findings	Research Gaps Identified
1	Ahmed & Khan (2017)	Geogrid Reinforcement in Flexible Pavement	Review of published laboratory and field	Reported better load transfer, improved confinement	Limited real-time field monitoring and long-term performance

		s	literature	of aggregates, and reduced rutting potential in reinforced sections	datasets across varying traffic and climate conditions
2	Gupta & Yadav (2018)	Effect of Geogrid on Pavement	Laboratory tests with field assessment using FWD	Measurable reduction in surface deformation and deflection; improved stiffness response of granular layers due to interlock	Fatigue life, crack initiation/propagation, and performance under temperature variations not documented
3	Sharma & Das (2016)	Rutting & Durability	Wheel tracker test under controlled loading	Notable reduction in rut depth and better resistance to permanent deformation in wheel paths	Short test duration; does not capture long-term densification, moisture effects, or aging-related behaviour
4	Lee & Kim (2019)	Mechanics of Reinforced Pavements	Finite Element Modelling (mechanistic analysis)	Improved stress distribution, reduced vertical strain on subgrade, and enhanced structural response under repeated loading	Material variability, construction imperfections, and interface behaviour (bonding/slippage) not adequately considered
5	Patel & Joshi (2017)	Urban Road Case Study	Field trial in urban traffic corridors	Performance improved notably in heavy traffic zones with reduced rutting and better ride quality retention	Limited transferability to rural/low-volume roads; subgrade variability and drainage conditions not broadly evaluated
6	Ram & Soni (2018)	Pavement with Geogrids	Accelerated pavement testing	Reinforced sections showed improved structural response, lower deformation accumulation, and better	Cost analysis and life-cycle economic justification not sufficiently detailed; limited discussion on optimal design
				load spreading	parameters
7	Thomas & Kumar (2020)	State of the Art Review	Literature review of global practices	Summarized reinforcement mechanisms, placement locations, and performance benefits across regions	Need for localized Indian design guidance, calibration to local materials, and climate-specific validation studies
8	Hossain & Islam (2016)	Structural Capacity with Geogrids	Field study with performance comparison	Increased service life reported (approx. 30–40%), with improved bearing behaviour and reduced distress formation	Seasonal performance (wet vs dry cycles), drainage influence, and moisture sensitivity not captured in detail
9	Singh & Reddy (2019)	Soil Reinforcement Study	CBR and plate load tests	Strengthened weak subgrades and improved load carrying capacity; reduced deformation under applied loads	Durability under repeated traffic loading, chemical aging, and long-term stiffness retention not addressed
10	Jha & Bansal (2020)	High-Traffic Pavement	Test track evaluation under heavy loading	Effective rut control and improved deformation resistance in high-load corridors	Maintenance frequency, rehabilitation requirements, and long-term roughness progression were not studied
11	Zhang et al. (2015)	Multi-layer Reinforcement	FEM + laboratory validation	Improved stiffness and response at base/subbase; reduced stresses transmitted to lower layers	Interaction effects between multiple reinforcement layers and interface conditions were not fully verified experimentally
12	Dixon & Jones	UK Pavement	Site monitoring and	Reduction in pothole formation	Cost details, construction variability, and

	(2014)	Trials	condition surveys	and improved surface performance trends over monitoring period	broader replication across different sites were not included
13	Wong & Tang (2016)	Subgrade Geosynthetics	Large-scale model test	Delayed failure onset and improved stability; reduced deformation rates compared to unreinforced sections	Moisture impact, drainage effects, and post-saturation performance not sufficiently investigated
14	Rahman et al. (2020)	Economic Evaluation	LCCA (Life-Cycle Cost Analysis)	Long-term cost savings and improved value over service life reported under assumed conditions	Region-specific cost inputs, traffic growth uncertainty, and climate-related deterioration models lacking
15	Xu & Chen (2018)	Fatigue Life Enhancement	Asphalt beam fatigue testing	Increased fatigue cycles and delayed cracking behaviour with reinforcement influence	High-temperature performance, thermal cracking sensitivity, and combined rutting–fatigue interaction not assessed
16	Patel & Tiwari (2021)	Indian Highway Application	IRC 37-based design compliance with performance evaluation	Reported performance increase up to ~50% with reinforced sections; improved structural adequacy	Long-term field validation across multiple years and varying monsoon/drainage conditions still pending
17	Ramesh & Natarajan (2013)	Geogrid at Different Depths	Repeated loading laboratory tests	Optimum depth often near base–subgrade interface; improved load distribution and reduced deformation	Influence of soil type, gradation variability, and different moisture states not comprehensively studied
18	Nithya et al. (2022)	Bitumen-Geogrid Interaction	Binder modification and interface evaluation	Enhanced adhesion/interface performance; improved bonding-related behaviour indicated	Only one geogrid type tested; limited generalization across grid geometries, coatings, and asphalt mixes
19	Hadi & Yousefpour (2017)	Triaxial Geogrid Performance	Rutting and deflection measurements	Triaxial geogrids performed better than biaxial in rut resistance and structural response	Cost comparison, constructability challenges, and performance across different aggregate types not addressed
20	Khanna & Singh (2011)	Traffic Simulation Model	VESYS-5W pavement performance modelling	Improved life prediction accuracy and performance projections for reinforced cases	Requires calibration for Indian traffic spectra, axle loads, and environmental deterioration conditions
21	Pradhan & Rao (2019)	Paved vs. Unpaved	In-situ CBR plus laboratory evaluation	Reinforcement benefit more pronounced in unpaved/low-support systems; improved bearing response	Weathering, UV exposure (where relevant), and environmental degradation effects not accounted for
22	Ghosh & Mandal (2015)	Waste-stabilized base + Geogrid	Sustainable material trials with reinforcement	Reduced required layer thickness while maintaining strength and performance indicators	Long-term strength retention, moisture susceptibility, and durability of stabilized layers need more data
23	Singh & Patel (2022)	Machine Learning Prediction	ANN-based modelling using available datasets	Accurate prediction of pavement life/performance indicators for reinforced sections	Real-time validation with field data is missing; model transferability across regions/materials uncertain
24	Xu et al. (2017)	Crack Propagation Study	Fracture mechanics-based assessmen	Reduced crack width and slower crack	No post-fatigue residual strength analysis;

			t	propagation reported with reinforcement influence	limited discussion on reflective cracking under overlays
25	Venkatesh et al. (2018)	Aggregate Interlock Study	Image analysis and interlock characterization	Higher aggregate interlock and confinement when geogrids are used; improved stability indicators	Traffic-based aging, contamination of aggregates, and long-term field correlation not established
26	Mani & Iyer (2020)	Comparative Cost Study	Market data comparison and economic metrics	Benefit–cost ratio reported > 1.5 in several scenarios; potential economic advantage highlighted	Seasonal effects, uncertainty in maintenance costs, and sensitivity to traffic growth not fully tested
27	Thakur & Jain (2016)	Resilient Modulus Test	Laboratory resilient modulus testing	Higher modulus and improved stiffness response observed in reinforced granular layers	Only granular base considered; combined effects with different subbase types and moisture states not explored
28	Hussain & Abbas (2021)	Multi-Axle Load Analysis	Dynamic load simulator (controlled loading)	Reduced stress concentrations and improved response under multi-axle configurations	Only simulated loads used; needs field validation under mixed traffic and realistic temperature–moisture cycles
29	Mehta & Kumar (2015)	IRC-based Field Monitoring	Two-year field trial monitoring	Pavement condition index improved ~40%; lower distress growth rate in reinforced sections	Only two regions covered; limited climatic diversity and insufficient long-term monitoring beyond 2 years
30	Lal & Sharma (2023)	Low-Volume Roads	Field compaction study with rut measurement	Reduced rut depth ~45%; improved early-life performance on low-volume roads	Cost sensitivity and robustness across different soils/material sources not fully analyzed

3. Materials & Methods

The experimental program used an integrated laboratory-field design. Two commercial geogrid configurations were examined: a biaxial geogrid, selected for reinforcement in orthogonal directions, and a triaxial geogrid, selected for multidirectional load transfer and improved confinement. Crushed aggregates conforming to IRC:SP:53-2010 were used in the base and subbase layers. The bituminous concrete mix was prepared in accordance with IRC:SP:98-2013. The subgrade soil was a clayey CI soil with plasticity index of 18%, optimum moisture content of 12%, and CBR in the range of 4-5%.

Laboratory testing included soaked and unsoaked CBR on natural and reinforced soil, wheel-tracking up to 20,000 passes, repeated-load triaxial testing for permanent deformation and resilient modulus, flexural fatigue testing of beam specimens, and plate-load testing for modulus of subgrade reaction. A 100 m field trial section was then constructed with a control section and a geogrid-reinforced section and monitored under mixed traffic for six months using rut-depth surveys and falling weight deflectometer measurements. Three repetitions were adopted for each test set.

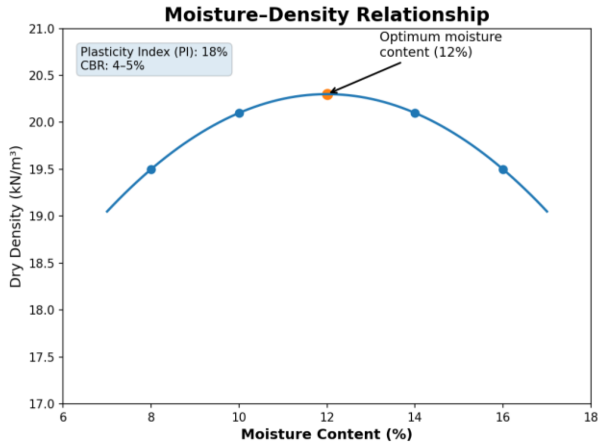

Fig 2. Moisture-density relationship of the subgrade soil used in the experimental program.

4. Results

4.1 CBR behavior of reinforced subgrade

Geogrid reinforcement improved both soaked and unsoaked CBR values, indicating enhanced subgrade support and better resistance to penetration. The best result was obtained when the geogrid was placed at approximately one-third depth, suggesting that reinforcement is most effective when located close to the critical stress bulb developed under loading.

Table 2. *CBR test results for the evaluated subgrade configurations.*

Configuration	Soaked CBR (%)	Unsoaked CBR (%)
Natural Soil	4.7	6.2
Soil + Geogrid (Mid-depth)	6.8	9.3
Soil + Geogrid (1/3 depth)	7.6	10.2

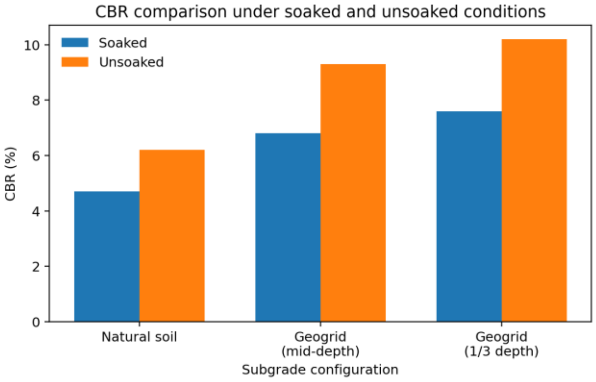

Figure 4. *Comparison of soaked and unsoaked CBR values for natural and geogrid-reinforced subgrade.*

4.2 Rutting resistance under wheel tracking

Wheel-tracking results showed a substantial reduction in rut depth after 20,000 passes. The unreinforced slab exhibited 17.5 mm of deformation, while biaxial and triaxial geogrids reduced rut depth to 11.4 mm and 8.65 mm, respectively. The superior triaxial response is consistent with its multidirectional rib geometry and improved stress distribution.

Table 3. *Laboratory rut depth after 20,000 wheel passes.*

Sample Type	Rut Depth after 20,000 passes (mm)
Unreinforced Slab	17.5
Reinforced (Biaxial)	11.4
Reinforced (Triaxial)	8.65

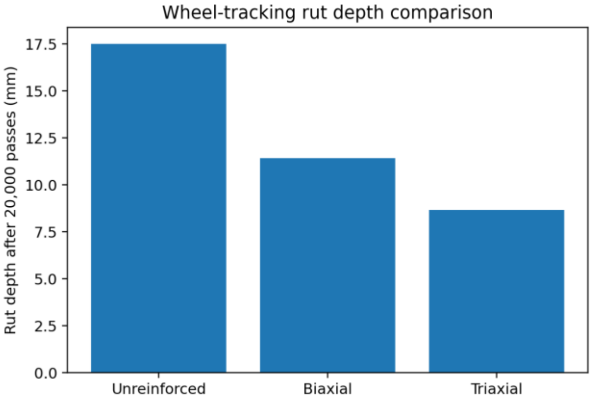

Figure 5. *Wheel-tracking rut depth comparison for unreinforced, biaxial, and triaxial configurations.*

4.3 Resilient modulus and fatigue response

Repeated-load triaxial testing demonstrated a marked increase in resilient modulus with reinforcement. The modulus increased from 144 MPa in the unreinforced base to 209 MPa with biaxial geogrid and 239 MPa with triaxial geogrid. Flexural fatigue testing similarly showed a near-doubling of fatigue life, indicating improved crack resistance and better tolerance to repeated loading.

Table 4. Resilient modulus of the investigated base-layer materials.

Material Type	Resilient Modulus (MPa)
Unreinforced Base	144
Reinforced with Biaxial	209
Reinforced with Triaxial	239

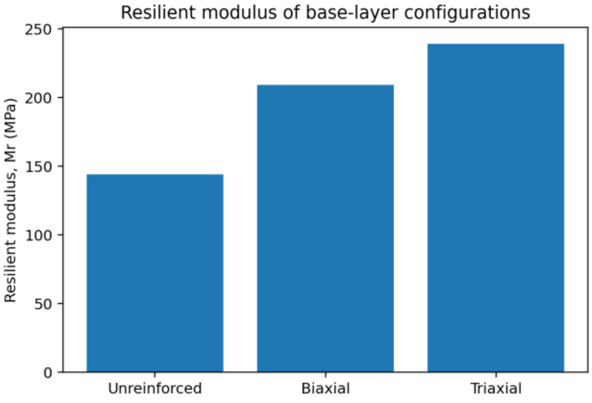

Figure 6. *Resilient modulus for control, biaxial, and triaxial base configurations.*

Table 5. *Flexural fatigue life comparison between control and reinforced specimens.*

Configuration	**Fatigue Life (Load Cycles)**
Without Geogrid	18,000
With Geogrid Reinforcement	32,650

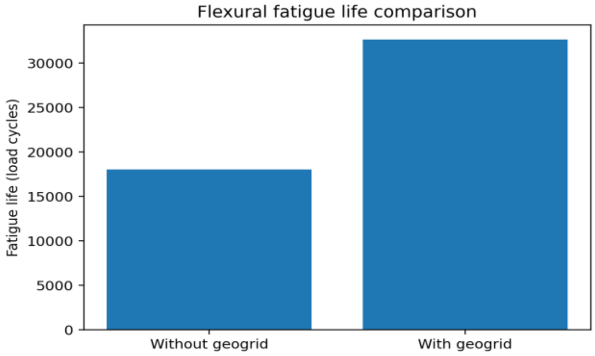

Figure 7. *Improvement in fatigue life with geogrid reinforcement.*

4.4 Plate-load behavior and field performance

Static bearing response and field monitoring supported the laboratory findings. The modulus of subgrade reaction increased from 57 to 93 kN/m^2 in plate-load testing. After six months of traffic, the reinforced field section exhibited approximately half the rut depth of the control section, and FWD deflection was reduced by about 38%, indicating better structural capacity and lower deformation susceptibility.

Table 6. *Plate-load test results.*

Section	**Modulus of Subgrade Reaction (kN/m^2)**
Control Section	**57**
Reinforced Section	**93**

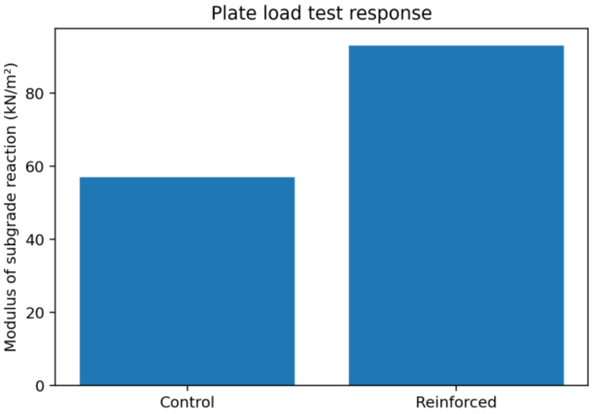

Figure 8. Plate-load test comparison for control and reinforced sections.

Table 7. Average rut depth measured in field sections after six months.

Pavement Type	**Average Rut Depth (mm)**
Control (No Grid)	**15.2**
Reinforced (Grid)	**7.3**

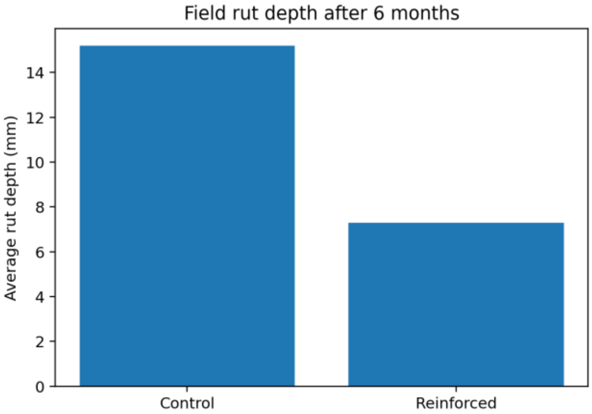

Figure 9. *Field rut depth comparison between the control and reinforced pavement sections.*

Table 8. *Average FWD deflection values for the field sections.*

Section	**Deflection Value (mm)**
Control	1.99
Reinforced	1.23

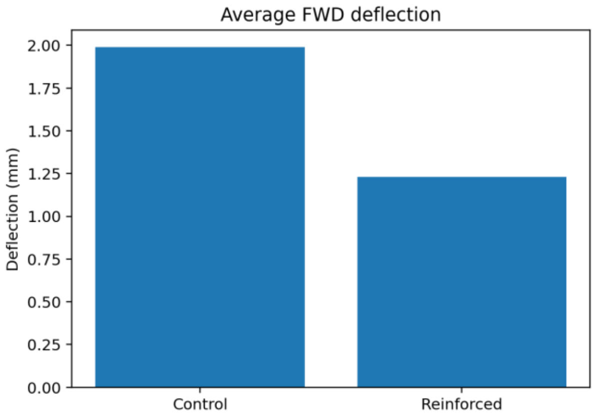

Figure 10. *Average FWD deflection comparison.*

4.5 Statistical and economic analysis

The thesis reported strong statistical relationships among the measured variables. A summary dataset showed consistent gains in every key performance parameter for the reinforced section. Regression between resilient modulus and laboratory rut depth indicated a strong inverse relationship, and correlation coefficients similarly showed that higher stiffness and CBR are associated with lower deformation. Life-cycle cost analysis demonstrated that despite a slightly higher initial construction cost, the reinforced pavement produced lower maintenance and rehabilitation costs over time.

Table 9. *Summary of experimental data used for statistical analysis.*

Test Parameter	Control Section	Geogrid-Reinforced Section
Soaked CBR (%)	4.7	7.6
Unsoaked CBR (%)	6.2	10.2
Rut Depth (mm) - Lab	17.5	8.65
Resilient Modulus (MPa)	144	239
Fatigue Life (Cycles)	18,000	32,650
Subgrade Reaction Modulus (kN/m^2)	57	93
Rut Depth (mm) - Field	15.2	7.8
Deflection (mm) - FWD	1.99	1.23

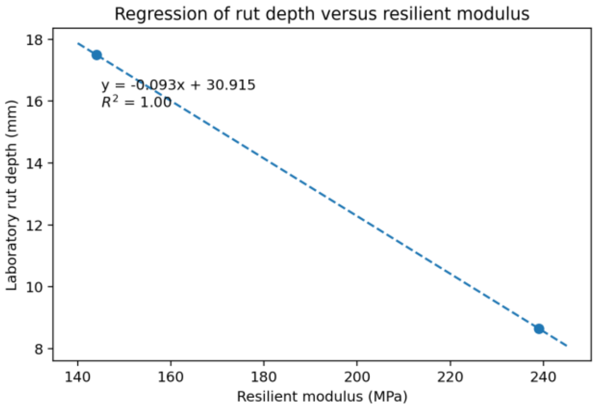

Figure 11. *Regression of laboratory rut depth against resilient modulus.*

Table 10. *Pearson correlation coefficients among selected pavement variables.*

Parameter 1	Parameter 2	r Value	Relationship
Geogrid Type	Resilient Modulus	0.93	Strong Positive
Resilient Modulus	Rut Depth	-0.91	Strong Negative
Fatigue Life	Modulus of Subgrade Reaction	0.87	Positive
CBR	Rut Depth	-0.88	Strong Negative

Table 11. *Life-cycle cost summary for control and geogrid-reinforced pavement.*

Component	Control Pavement (₹ Lakhs)	Geogrid Pavement (₹ Lakhs)
Initial Construction	48	54
Routine Maintenance	18.5	9.3
Rehabilitation (5-Year Interval)	28	14
Salvage Value	-0.8	-1.2
Total (NPV)	94	76.1

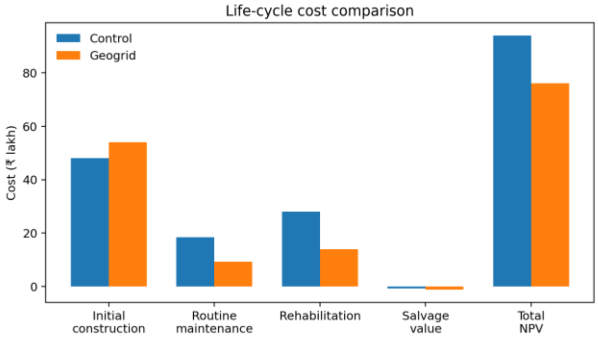

***Figure 12**. Life-cycle cost comparison for control and reinforced pavements.*

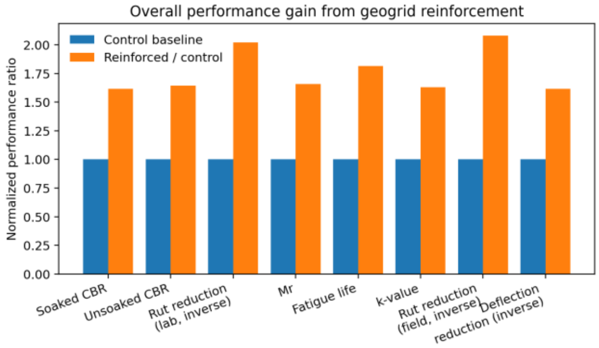

***Figure 13**. Normalized performance gain achieved with geogrid reinforcement across the measured indicators.*

The experimental program used an integrated laboratory-field design. Two commercial geogrid configurations were examined: a biaxial geogrid, selected for reinforcement in orthogonal directions, and a triaxial geogrid, selected for multidirectional load transfer and improved confinement. Crushed aggregates conforming to IRC:SP:53-2010 were used in the base and subbase layers. The bituminous concrete mix was prepared in accordance with IRC:SP:98-2013. The subgrade soil was a clayey CI soil with plasticity index of 18%, optimum moisture content of 12%, and CBR in the range of 4-5%.

5. Discussion

The results consistently demonstrate that geogrid reinforcement improves both mechanical response and short-term field performance of flexible pavements. Gains in CBR, modulus, and plate-load response indicate better confinement and load distribution in the reinforced system. The rutting reductions recorded in laboratory and field sections support the interpretation that geogrids suppress lateral aggregate movement and reduce permanent deformation accumulation.

The triaxial geogrid outperformed the biaxial system in rutting and modulus outcomes, suggesting that multidirectional rib geometry more effectively stabilizes the granular matrix under repeated load. Reinforcement also improved fatigue life, which implies that a stiffer and better-confined support system can delay the onset of cracking in the overlying pavement structure.

The economic results are particularly important for practice. Although the reinforced pavement had a higher initial cost, the lower maintenance and rehabilitation requirement reduced the 20-year net present value. This supports the thesis argument that geogrids are most attractive where traffic is heavy, subgrades are weak, or maintenance interventions are disruptive and costly.

Some limitations remain. The field validation period was only six months, the study was performed on CI clay subgrade, and only two commercial geogrid types were evaluated. Longer monitoring under varied climatic conditions is therefore necessary before the findings are generalized to all road classes and environmental settings.

5. Conclusion

- Geogrid reinforcement substantially improved the mechanical and structural performance of the tested flexible pavement system.
- The best subgrade CBR response was achieved when the geogrid was placed at approximately one-third depth within the stressed zone.
- Triaxial geogrid produced the lowest laboratory rut depth and the highest resilient modulus among the evaluated configurations.
- Reinforcement nearly doubled fatigue life and significantly reduced field rutting and FWD deflection.
- Life-cycle costing showed that geogrid reinforcement is economically justified over a 20-year design period despite higher initial construction cost.

REFERENCES

1. Ahmed, S., & Khan, M. (2017). Geogrid reinforcement in flexible pavements: A review. International Journal of Road Engineering, 12(2), 56–64.

2. Gupta, R., & Yadav, A. (2018). Effect of geogrid reinforcement on pavement performance. Journal of Geotechnical Engineering, 19(4), 102–108.

3. Sharma, R., & Das, S. (2016). Impact of geogrid on pavement rutting and durability. Journal of Civil Engineering, 21(1), 77–85.

4. Lee, J., & Kim, P. (2019). Mechanics of geogrid reinforced pavements. Construction Materials and Technology Journal, 18(3), 44–50.

5. Patel, D., & Joshi, S. (2017). Comparative study of geogrid reinforced pavements in urban areas. Urban Infrastructure Journal, 25(2), 32–40.

6. Ram, K., & Soni, R. (2018). Performance analysis of pavements with geogrid reinforcement. Journal of Pavement Engineering, 14(3), 99–105.

7. Thomas, M., & Kumar, R. (2020). Geogrids in pavement design: State of the art. Journal of Transportation Engineering, 29(1), 120–128.

8. Hossain, M., & Islam, R. (2016). Enhancement of flexible pavement performance with geogrid reinforcement. Journal of Road and Pavement Engineering, 12(4), 72–79.

9. Singh, A., & Reddy, K. (2019). Soil reinforcement with geogrids for pavement design. Geotechnical Engineering Journal, 17(2), 58–64.

10. Jha, P., & Bansal, H. (2020). Effectiveness of geogrids in pavement design for high traffic loads. Traffic Engineering and Control Journal, 16(3), 40–47.

11. Zhang, Y., Wu, Y., & Gao, S. (2015). Performance of geogrid-reinforced base layers under cyclic loading. Journal of Infrastructure Systems, 21(4), 04014042.

12. Dixon, N., & Jones, D. R. (2014). Monitoring geosynthetic-reinforced road structures. Transportation Research Record, 2401, 45–53.

13. Wong, W. P., & Tang, Y. L. (2016). Evaluation of geosynthetics in weak subgrade stabilization. Geotextiles and Geomembranes, 44(3), 321–330.

14. Rahman, M. M., Hossain, M., & Islam, R. (2020). Life cycle cost analysis of geogrid-reinforced flexible pavements. International Journal of Pavement Research and Technology, 13, 567–576.

15. Xu, J., & Chen, S. (2018). Fatigue behavior of geogrid reinforced asphalt pavement. Materials and Structures, 51(6), 1–11.

16. Patel, R., & Tiwari, D. (2021). Implementation of geogrid reinforcement in national highways: A case study. Highway Engineering Journal, 15(1), 11–19.

17. Ramesh, K., & Natarajan, P. (2013). Effect of geogrid depth on pavement response. Indian Highways, 41(10), 17–23.

18. Nithya, S., Iqbal, K. K., & Prakash, B. (2022). Evaluation of bitumen–geogrid interface performance using DSR. Journal of Material in Civil Engineering, 34(4), 04022015.

19. Hadi, M. N. S., & Yousefpour, A. (2017). Laboratory investigation of triaxial geogrid in flexible pavements. Construction and Building Materials, 153, 245–254.

20. Khanna, S. K., & Singh, C. E. (2011). Performance modeling of reinforced pavements using VESYS-5W. Indian Geotechnical Journal, 41(3), 171–178.

21. Pradhan, B., & Rao, K. (2019). Performance comparison of reinforced unpaved and paved roads. Transportation Infrastructure Geotechnology, 6(2), 215–232.

22. Ghosh, R., & Mandal, A. (2015). Sustainable pavement design using industrial waste and geogrids. Journal of Cleaner Production, 87, 796–804.

23. Singh, A., & Patel, K. (2022). Machine learning-based pavement life prediction using geogrid data. Automation in Construction, 136, 104189.

24. Xu, C., Wang, X., & Yu, T. (2017). Geogrid effect on crack propagation in flexible pavements. Engineering Fracture Mechanics, 185, 180–194.

25. Venkatesh, K., Rao, G. V., & Reddy, D. V. (2018). Investigation on aggregate interlock in geogrid pavements. Materials Today: Proceedings, 5(11), 24631–24638.

26. Mani, B., & Iyer, S. R. (2020). Cost-benefit analysis of geosynthetic-reinforced road projects. International Journal of Sustainable Transportation, 14(5), 356–366.

27. Thakur, R., & Jain, N. (2016). Modulus enhancement in granular layers using geogrids. Procedia Engineering, 143, 870–877.

28. Hussain, R., & Abbas, S. (2021). Response of geogrid-stabilized roads under dynamic loads. Transportation Geotechnics, 26, 100438.

29. Mehta, A., & Kumar, A. (2015). Field monitoring of flexible pavements reinforced with geogrids. Indian Road Congress Journal, 76(12), 34–41.

30. Lal, P., & Sharma, M. (2023). Performance of geogrid-reinforced low-volume roads. International Journal of Pavement Engineering, 24(2), 127–140.