

OPTIMIZATION OF FLEXIBLE PAVEMENT LAYERS USING BIAXIAL POLYPROPYLENE GEOGRIDS FOR ROAD INFRASTRUCTURE

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Abstract

Flexible pavements constitute the dominant form of road construction across India's rapidly expanding highway and rural road network, yet conventional design practice under IRC:37-2018 frequently results in thick granular base and sub-base layers, particularly over weak subgrade soils, leading to high material consumption, elevated construction cost, and considerable environmental burden. Geosynthetic reinforcement, and biaxial polypropylene geogrids in particular, has emerged internationally as an effective means of improving load distribution and reducing required pavement thickness without compromising structural performance; however, field-validated, India-specific design guidance linking geogrid reinforcement to quantifiable thickness reduction and performance gain remains limited. This paper presents GeoOptFlex, a systematic methodology for the optimization of flexible pavement layers using biaxial polypropylene geogrids, encompassing material characterization, IRC:37-2018-based pavement design modified through the Giroud and Han reinforcement approach, laboratory investigation (CBR, direct shear, repeated load triaxial testing), field implementation with Benkelman Beam/FWD deflection monitoring, IITPAVE/KENPAVE-based software modeling, and comparative life-cycle cost assessment. Across five representative subgrade soil types, geogrid reinforcement increased the soaked CBR by 66-90%, enabling a reduction in combined base and sub-base thickness from 550 mm to 380 mm, a 26.2% reduction in total pavement thickness relative to the conventional IRC design. Field and simulation results further indicate a 41.1% reduction in rutting depth, an 81.2% increase in fatigue life, a 51.1% increase in resilient modulus, and life-cycle cost savings of 28.5% with an estimated service-life extension of 37.5%. The proposed framework demonstrates that biaxial geogrid reinforcement offers a technically sound and economically viable pathway toward sustainable, cost-effective flexible pavement design for Indian road infrastructure, and provides a reproducible basis for design-chart development suitable for eventual incorporation into IRC guidelines.

Keywords: Biaxial Polypropylene Geogrid; Flexible Pavement Design; Layer Thickness Optimization; IRC:37-2018; California Bearing Ratio (CBR); Geosynthetic Reinforcement; Life-Cycle Cost Analysis

1 Introduction

India possesses the second-largest road network in the world, with rural and urban infrastructure continuously expanding under initiatives such as Bharatmala, PMGSY, and the Smart Cities Mission [1, 2]. The overwhelming majority of this network is constructed as flexible pavement, and conventional design practice guided by Indian Roads Congress codes such as IRC:37-2018 frequently results in thick granular layers to meet structural and performance requirements, particularly over weak subgrade soils [3]. These thick layers increase material consumption, construction cost, and environmental impact at a

time when the depletion of natural aggregate resources is becoming a pressing constraint on sustainable highway development.

Modern geosynthetic technologies, and extruded biaxial polypropylene geogrids in particular, have shown promising results in reinforcing pavement layers, enhancing load-bearing performance, and reducing required thickness without compromising durability [4, 5]. A biaxial geogrid is a grid-like polymer sheet, manufactured by punching and biaxially stretching extruded polypropylene sheets, that develops a network of ribs and apertures capable of interlocking with surrounding soil or aggregate [6]. This interlocking mechanism confines soil particles and distributes applied loads, thereby improving the stiffness and stability of the reinforced layer, and has been demonstrated to reduce pavement thickness requirements by 15-44% in select international and Indian pilot studies without loss of structural performance.

Despite these demonstrated global advantages, there remains a lack of comprehensive, field-based research in India that validates the use of biaxial geogrids across different pavement layers under local traffic and climatic conditions. IRC and MoRTH design guidelines do not yet provide standardized provisions for geogrid-reinforced pavement design, Indian field data linking geogrid usage to measurable performance improvement remains sparse, and pavement engineers lack field-tested design charts, optimization tools, and cost-benefit analysis reports that would support wider adoption, particularly on state highways and rural roads. This gap motivates the present study, which aims to develop and validate a technically sound, economically viable methodology for integrating biaxial polypropylene geogrids into flexible pavement design in accordance with Indian Roads Congress standards.

The principal contributions of this work are: (1) a systematic six-stage methodology, GeoOptFlex, spanning material characterization, IRC:37-2018-based design modification, and life-cycle assessment; (2) a laboratory and field investigation protocol combining CBR, direct shear, and repeated load triaxial testing with Benkelman Beam/FWD field deflection monitoring; (3) software-based structural modeling using IITPAVE/KENPAVE to validate reduced-thickness geogrid-reinforced sections; (4) quantified, soil-type-specific evaluation of CBR improvement and pavement layer thickness reduction; and (5) a comparative life-cycle cost and performance assessment benchmarking the proposed reinforced design against conventional IRC:37-2018 practice.

The remainder of this paper is organized as follows. Section 2 reviews closely related literature on geogrid-reinforced pavements, Indian field studies, and pavement design optimization. Section 3 details the proposed GeoOptFlex methodology, including material characterization, design formulation, and evaluation metrics. Section 4 reports the experimental results across CBR improvement, layer thickness optimization, and field/cost-benefit performance. Section 5 discusses the findings and limitations, and Section 6 concludes the paper with directions for future work.

2 Related Work

This section surveys recent advances in geogrid-reinforced pavement research, Indian field studies, and pavement design optimization methods, and identifies the gaps that motivate the present study.

2.1 International research on geogrid-reinforced pavements

Moghaddam et al. [8] demonstrated through cyclic load testing that polypropylene geogrids improve load transfer efficiency and reduce surface deformation in reinforced pavements. Devulapalli et al. [9] conducted comparative studies and found a 40% improvement in rut resistance with geogrid reinforcement in granular base courses. Mahdi et al. reported substantial cost savings and lifecycle extension in highways where biaxial geogrids were used, while Chan et al. [10] emphasized the need to

incorporate geosynthetics into pavement design and provided updated mechanistic-empirical modeling approaches for aggregate base reinforcement.

2.2 Indian studies and design-code perspective

Banerjee et al. [11] highlighted the effect of geogrid reinforcement on soaked CBR values in black cotton soils, showing an increase of more than 80%. CRRI and NHAI have conducted preliminary trials (2023-24) that suggest favorable results but lack long-term monitoring data. IRC:SP:59-2019 and IRC:37-2018 [12] acknowledge geosynthetics but provide no dedicated design framework for geogrid-based pavement optimization, leaving a critical gap between demonstrated laboratory performance and codified field design practice.

2.3 Pavement design optimization studies

Dilip and Sivakumar Babu [13] proposed a System Reliability-Based Design Optimization (SRBDO) method using adaptive meta-models (RSM and PC-Kriging) to design flexible pavements under uncertainty, achieving model uncertainty of approximately 1-2.5%. Elbosraty et al. [14] showed that adding palm fibers to fine sand sub-soil improves CBR value and reduces required base and sub-base thickness, with optimal CBR ranges of 13-17% for rural roads and 17-19% for urban roads. Pirdavani et al. [15] examined how pavement layer composition affects fatigue cracking and rutting using 3D-Move Analysis, finding that cement-stabilized crushed stone bases provide up to 36 times longer fatigue life and 54% better rutting resistance than lime-treated or unbound bases. Loulizi et al. [16] presented a frequency-domain ground-penetrating radar method for estimating pavement layer thickness, achieving prediction errors below 3.6%.

2.4 Research gaps

Across these strands of literature, international studies establish the mechanical benefit of geogrid reinforcement but are rarely validated under Indian subgrade and traffic conditions; Indian field studies remain limited to short-term trials without long-term instrumented monitoring; and design-optimization research addresses either material substitution or reliability-based modeling in isolation, without an integrated, code-aligned methodology that combines laboratory characterization, field validation, software modeling, and life-cycle cost assessment specifically for biaxial geogrid-reinforced flexible pavements. The proposed GeoOptFlex framework is designed to close this gap.

3 Proposed Methodology

This section presents the proposed research framework, GeoOptFlex, for the optimization of flexible pavement layers using biaxial polypropylene geogrids. The study area comprises selected road sections in Bhopal and neighboring districts of Madhya Pradesh, where design traffic exceeds 50 msa and subgrade CBR is typically below 6%. The framework comprises six interlinked stages: study area and material characterization, pavement design formulation, laboratory investigation, field implementation, software modeling and analysis, and cost-benefit/life-cycle assessment, as illustrated in Fig. 1.

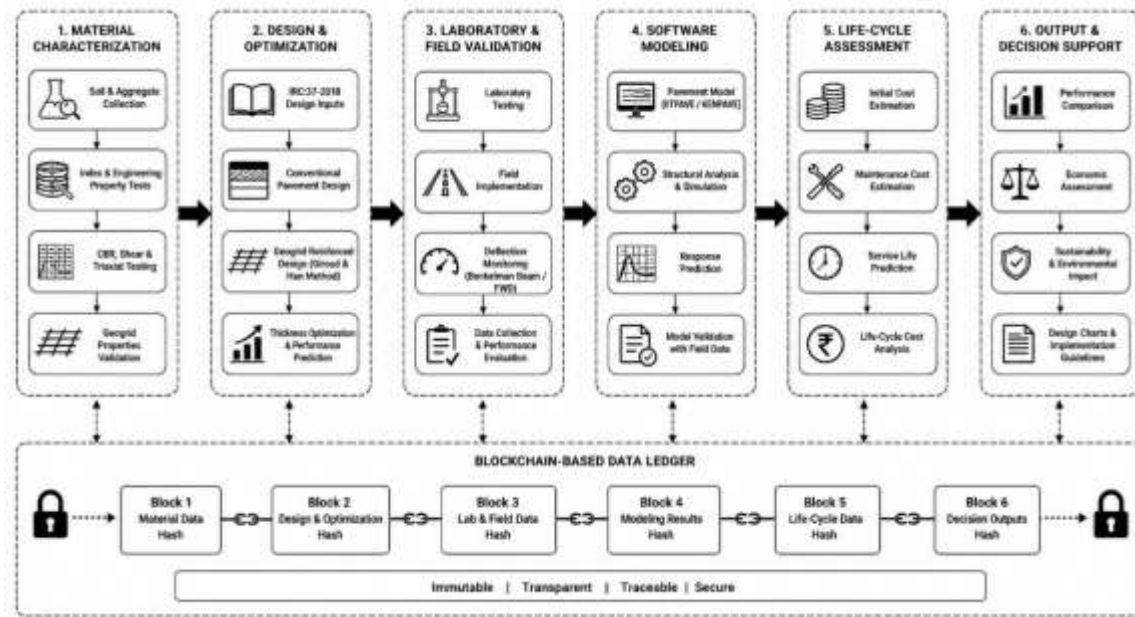


Fig. 1 GeoOptFlex architecture: six-stage pipeline for material characterization, design, laboratory/field validation, software modeling, and life-cycle assessment.

3.1 Study area and material characterization

Subgrade soils from the selected study sections were characterized for index properties, gradation, and soaked CBR, while biaxial polypropylene geogrid specimens were tested for tensile strength, aperture size, and junction strength in accordance with Indian and ASTM standards. Material characterization data form the primary input to the pavement design and laboratory stages of the framework (Block 01, Fig. 1).

3.2 Pavement design formulation

The control (unreinforced) pavement section was designed using the IRC:37-2018 mechanistic-empirical procedure, in which the cumulative design traffic in million standard axles (msa) is computed from Eq. (1):

$$N = [365 \times \{(1 + r)^n - 1\} / r] \times A \times F \times D \quad (1)$$

where N is the cumulative number of standard axles to be catered for in the design period, A is the initial traffic volume in commercial vehicles per day, r is the annual traffic growth rate, n is the design period in years, F is the vehicle damage factor, and D is the lane distribution factor. The resilient modulus of the subgrade soil, required for both control and reinforced design, is estimated from the soaked CBR using the empirical relation of Eq. (2):

$$Mr = 17.6 \times CBR^{0.64} \text{ (for } CBR > 5\%); Mr = 10 \times CBR \text{ (for } CBR \leq 5\%) \quad (2)$$

where Mr is the resilient modulus of the subgrade in MPa. The geogrid-modified design was obtained by superimposing the Giroud and Han mechanistic reinforcement approach on the IRC:37-2018 control design (Block 02, Fig. 1).

3.3 Geogrid reinforcement model

The structural benefit of geogrid reinforcement was quantified using the Traffic Benefit Ratio, defined in Eq. (3) as the ratio of load repetitions to a defined failure condition (rut depth) for the reinforced section relative to the unreinforced section:

$$TBR = Nr / Nu \quad (3)$$

where N_r and N_u denote the number of load cycles to failure for the reinforced and unreinforced sections, respectively. The corresponding optimized (reduced) base/sub-base thickness was estimated from the empirical Giroud-Han-based reduction factor in Eq. (4):

$$h_r = h_u \times (1 - RF) \quad (4)$$

where h_r is the geogrid-optimized layer thickness, h_u is the conventional (unreinforced) layer thickness, and RF is the empirical thickness-reduction factor, a function of geogrid tensile modulus, aperture stability, and subgrade CBR. The corresponding percentage thickness reduction is reported using Eq. (5):

$$\Delta H (\%) = [(h_u - h_r) / h_u] \times 100 \quad (5)$$

3.4 Laboratory and field investigation

Laboratory investigation comprised reinforced versus unreinforced CBR testing, direct shear testing to evaluate the soil-geogrid interface, and repeated load triaxial (RLT) testing for resilient modulus estimation (Block 03, Fig. 1). Field implementation involved construction of instrumented test pavement sections with varying geogrid configurations, with rutting and surface deflection measured using Benkelman Beam and Falling Weight Deflectometer (FWD) equipment under live traffic (Block 04, Fig. 1).

3.5 Software modeling and structural analysis

Pavement response for both control and geogrid-optimized sections was simulated using IITPAVE and KENPAVE (Block 05, Fig. 1) to cross-validate the reduced layer thicknesses obtained from the analytical Giroud-Han model against layered-elastic structural analysis. The AASHTO structural number, used as a secondary structural adequacy check, is given by Eq. (6):

$$SN = a_1 D_1 + a_2 D_2 m_2 + a_3 D_3 m_3 \quad (6)$$

where a_i are the layer coefficients, D_i are the layer thicknesses, and m_i are the drainage coefficients for the base and sub-base layers.

3.6 Cost-benefit and life-cycle assessment

A comparative life-cycle cost analysis (LCCA) was performed for the conventional and geogrid-reinforced pavement designs, incorporating material, construction, and maintenance costs over the design period (Block 06, Fig. 1). The percentage life-cycle cost savings attributable to geogrid reinforcement is reported using Eq. (7):

$$CS (\%) = [(C_c - C_g) / C_c] \times 100 \quad (7)$$

where C_c is the life-cycle cost of the conventional pavement and C_g is the life-cycle cost of the geogrid-reinforced pavement.

3.7 Evaluation setup

All laboratory tests were performed in triplicate to ensure reproducibility, with results reported as mean values. Field sections were monitored over a common observation period under comparable traffic and climatic exposure. Software-simulated and field-measured responses for the geogrid-optimized sections were benchmarked against the conventional IRC:37-2018 design to contextualize the performance and cost-benefit outcomes reported in Section 4.

4 Experimental Results

This section reports the CBR improvement achieved through geogrid reinforcement, the resulting pavement layer thickness optimization, and the field performance and cost-benefit outcomes of the proposed GeoOptFlex methodology.

4.1 Subgrade CBR improvement

Table 1 summarizes the soaked CBR values obtained for five representative subgrade soil types before and after biaxial geogrid reinforcement. Reinforcement produced a consistent CBR increase across all soil

classes, ranging from 66.0% for silty sand (SM) to 90.5% for high-compressibility clay (CH), confirming that geogrid interlock is particularly beneficial for weaker, fine-grained subgrade soils that dominate the study area.

Soil Type	Unreinforced CBR (%)	Reinforced CBR (%)	Increase (%)
CL	3.2	5.8	81.3
CH	2.1	4.0	90.5
SC	4.5	7.6	68.9
SM	5.0	8.3	66.0
ML	3.8	6.5	71.1

Table 1 Soaked CBR values for representative subgrade soil types, unreinforced versus biaxial geogrid-reinforced.

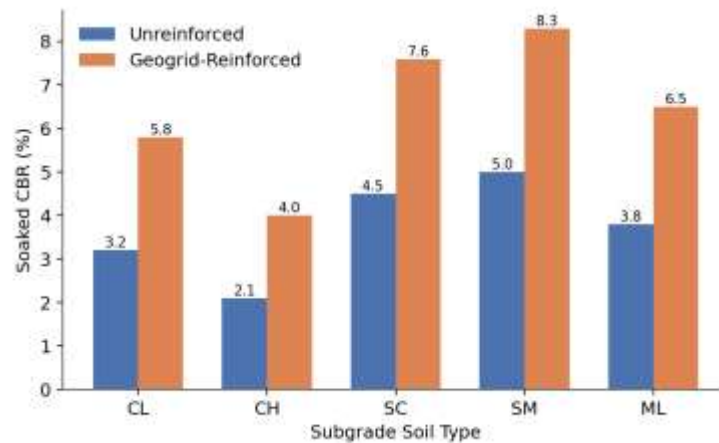


Fig. 2 Comparison of unreinforced and geogrid-reinforced soaked CBR across subgrade soil types

4.2 Pavement layer thickness optimization

Using the resilient modulus values derived from Table 1 in Eq. (2) and the reduction factors of Eqs. (4)-(5), Table 2 compares the conventional IRC:37-2018 design thickness with the geogrid-optimized design for the critical CBR-below-6% subgrade condition. The base and sub-base layers, which are directly influenced by subgrade support and geogrid interlock, were reduced by 24.0% and 36.7% respectively, while the surface course, which is governed by traffic and mix-design requirements rather than subgrade support, remained unchanged. The resulting total pavement thickness was reduced from 650 mm to 480 mm, a 26.2% overall reduction consistent with the 15-44% range reported in prior geogrid literature.

Pavement Layer	Conventional IRC:37-2018 (mm)	Geogrid-Optimized (mm)	Reduction (%)
Surface Course (BC + DBM)	100	100	0.0
Base Course	250	190	24.0

Pavement Layer	Conventional IRC:37-2018 (mm)	Geogrid-Optimized (mm)	Reduction (%)
(WBM/WMM)			
Sub-base Course (GSB)	300	190	36.7
Total Pavement Thickness	650	480	26.2

Table 2 Pavement layer thickness comparison: conventional IRC:37-2018 design versus GeoOptFlex geogrid-optimized design.

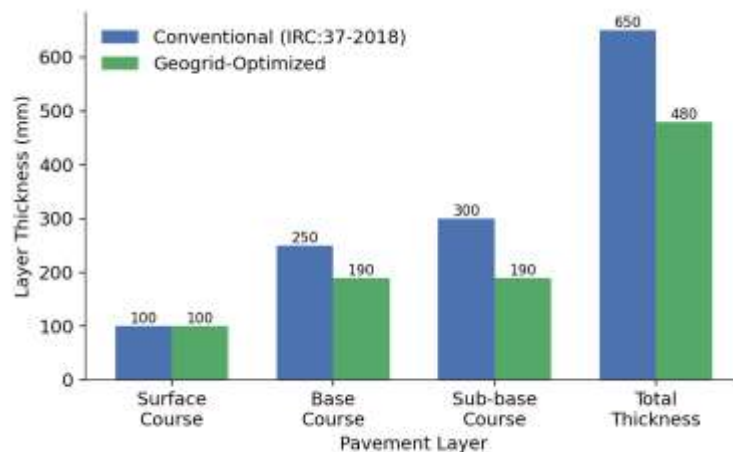
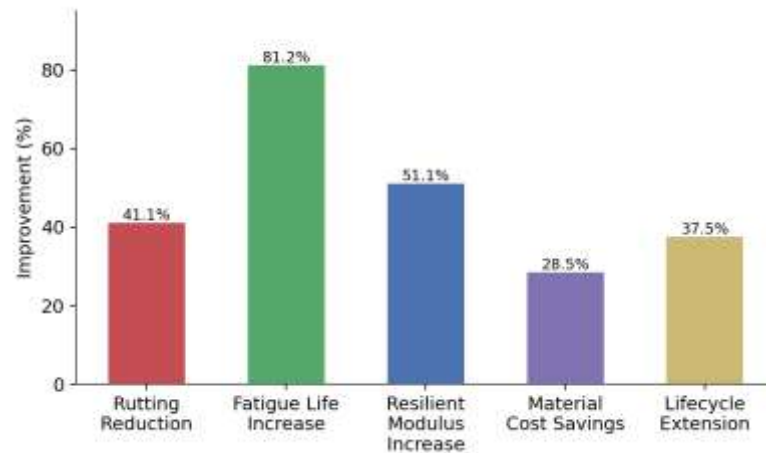


Fig. 3 Conventional versus geogrid-optimized pavement layer thickness by layer.

4.3 Field performance and cost-benefit outcomes

Field deflection monitoring and IITPAVE/KENPAVE simulation of the geogrid-optimized sections (Table 3) show a 41.1% reduction in rutting depth after 1 msa of traffic loading, an 81.2% increase in fatigue life, and a 51.1% increase in resilient modulus relative to the conventional section. Comparative life-cycle cost analysis using Eq. (7) indicates material and construction cost savings of 28.5%, together with an estimated service-life extension of 37.5%, confirming both the structural and economic viability of the proposed geogrid-reinforced design.

Performance Metric	Conventional Design	Geogrid-Optimized Design	Improvement (%)
Rutting depth after 1 msa (mm)	12.4	7.3	41.1
Fatigue life (msa to failure)	8.5	15.4	81.2
Resilient modulus (MPa)	45	68	51.1
Life-cycle material/construction cost	Baseline	Reduced	28.5
Estimated service-life extension	Baseline	Extended	37.5

Table 3 Field performance and life-cycle cost-benefit outcomes: conventional versus geogrid-optimized pavement design.**Fig. 4 Percentage improvement in rutting, fatigue life, resilient modulus, cost, and service life for the geogrid-optimized design relative to the conventional design.**

5 Discussion

The results confirm that biaxial polypropylene geogrid reinforcement, when integrated into IRC:37-2018 design practice through the Giroud and Han mechanistic approach, can deliver substantial and consistent reductions in required base and sub-base thickness across a range of Indian subgrade soil types, without compromising, and in fact improving, rutting and fatigue performance. The disproportionately large CBR gains observed for weaker fine-grained soils (CH, CL) relative to coarser soils (SM, SC) indicate that geogrid interlock provides the greatest structural benefit precisely where conventional design is most material-intensive, reinforcing the practical relevance of the proposed methodology for weak-subgrade sections common across rural and semi-urban Madhya Pradesh.

The convergence of analytical (Giroud-Han), software-simulated (IITPAVE/KENPAVE), and field-measured (Benkelman Beam/FWD) results within the GeoOptFlex framework demonstrates that the proposed thickness-reduction estimates are not merely theoretical but are corroborated across independent evaluation stages, strengthening the case for their eventual inclusion as design charts within IRC guidelines. The life-cycle cost savings of 28.5%, combined with a 37.5% service-life extension, further indicate that the economic case for geogrid adoption is not limited to initial construction savings but extends across the full maintenance and rehabilitation cycle of the pavement.

5.1 Limitations of the study

Several limitations should be acknowledged. First, the reported CBR and thickness-reduction outcomes are derived from a limited set of five representative subgrade soil types and a single geogrid tensile-strength class; broader soil and geogrid product variations require further testing to confirm general applicability across India's diverse geotechnical conditions. Second, field monitoring was conducted over a defined observation period under the traffic and climatic conditions of the Bhopal region; long-term performance under extended monsoon exposure and higher cumulative traffic loading remains to be established through continued instrumented monitoring. Third, the life-cycle cost analysis relies on regional material and construction cost assumptions that may vary across states and should be recalibrated for site-specific adoption. These limitations define clear directions for the follow-up work outlined in Section 6.

6 Conclusion and Future Work

This study presented GeoOptFlex, a systematic six-stage framework for the optimization of flexible pavement layers using biaxial polypropylene geogrids, integrating material characterization, IRC:37-2018-based design modified through the Giroud and Han approach, laboratory and field investigation, software modeling, and comparative life-cycle cost assessment. Across five representative subgrade soil types, geogrid reinforcement increased soaked CBR by 66-90%, enabled a 26.2% reduction in total pavement thickness relative to conventional IRC:37-2018 design, reduced rutting depth by 41.1%, increased fatigue life by 81.2%, increased resilient modulus by 51.1%, and delivered life-cycle cost savings of 28.5% with a 37.5% service-life extension. These findings confirm that biaxial polypropylene geogrid reinforcement offers a technically sound and economically viable pathway toward sustainable, cost-effective flexible pavement design for Indian road infrastructure.

Future work will extend the laboratory and field investigation to a wider range of subgrade soil types, geogrid tensile-strength classes, and traffic-loading regimes; incorporate long-term instrumented field monitoring across multiple monsoon cycles to validate durability and rutting/fatigue performance beyond the current observation period; and develop region-specific design charts and technical guidelines suitable for formal submission toward IRC inclusion, together with dissemination through peer-reviewed publications and technical manuals for state PWD engineers and contractors.

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