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Development of a Comprehensive Computational Framework for Evaluating Geogrid Reinforcement Effectiveness in Flexible Pavement Design

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Abstract: Flexible pavements face increasing deterioration under growing traffic loads and adverse environmental conditions. This study develops a comprehensive computational framework for evaluating geogrid reinforcement effectiveness in flexible pavement performance through synthetic data modeling and statistical analysis. The research methodology involves creating a Python-based analytical tool that generates realistic synthetic datasets representing various pavement configurations. The framework encompasses multiple geogrid types (unreinforced, uniaxial, biaxial, and triaxial) across diverse soil conditions and traffic loading scenarios. Key performance parameters include rutting depth, fatigue life, bearing capacity, resilient modulus, settlement characteristics, and integrated performance indices. The analytical framework employs advanced statistical techniques including ANOVA, correlation analysis, and machine learning algorithms for predictive modeling. Comprehensive data visualization capabilities enable three-dimensional surface plotting and cost-benefit analysis for design optimization. The synthetic data generation is based on established pavement engineering principles and documented geogrid performance relationships. This computational methodology provides pavement engineers with a robust tool for preliminary design evaluation and parameter sensitivity analysis. The framework enables systematic exploration of design alternatives that may be difficult to test under field conditions. The research contributes an accessible analytical platform for evidence-based geogrid reinforcement design decisions and establishes foundations for future validation studies against field performance data.
Keywords: Geogrid Reinforcement; ANOVA; correlation analysis; machine learning

I. INTRODUCTION

Flexible pavements form the backbone of surface transportation infrastructure worldwide, especially in developing countries where climatic extremes and rising traffic volumes accelerate their deterioration. These pavements are often subjected to repetitive loading from increasingly heavy commercial vehicles, leading to critical distress mechanisms such as rutting, fatigue cracking, and surface settlement. Over time, such degradations compromise not only the structural integrity of the pavement but also user safety, comfort, and economic efficiency. Traditional pavement designs, although widely used, are often insufficient to address these complex and evolving challenges, particularly in subgrade conditions with poor load-bearing capacity. In response, geosynthetic reinforcements—especially geogrids—have emerged as a promising intervention to enhance pavement performance. Geogrids are polymer-based grids that, when integrated within pavement layers, improve load distribution, minimize deformations, and prolong pavement service life. Various configurations such as uniaxial, biaxial, and triaxial geogrids offer tailored mechanical benefits, but their selection and design application remain highly context-dependent. While numerous laboratory tests and field trials have demonstrated their effectiveness, conducting such empirical studies at scale is both time-consuming and cost-intensive. Moreover, the interactions between geogrid types, soil properties, pavement structure, and traffic loading scenarios are highly nonlinear, making it difficult to generalize performance outcomes. This research is motivated by the need to develop an efficient, scalable, and computationally grounded methodology for evaluating geogrid reinforcement in flexible pavements [1-5]. By leveraging synthetic data modeling grounded in established engineering principles, coupled with statistical analysis and machine learning, this study aims to overcome the limitations of field experimentation and provide engineers with a powerful analytical tool. The motivation also stems from a growing recognition of the need for evidence-based, cost-effective pavement design practices that account for the complex interplay of materials, mechanics, and external conditions. As the demand for resilient and sustainable infrastructure grows, the integration of computational tools for preliminary assessment and decision-making becomes not only advantageous but essential. Therefore, this work intends to bridge the gap between theoretical knowledge, empirical findings, and practical design needs through a unified, accessible analytical framework [6-10].

Despite the proven benefits of geogrid reinforcement in enhancing the structural performance and longevity of flexible pavements, the current design and evaluation practices remain largely empirical, fragmented, and limited in scope. Most existing methods rely heavily on field trials and laboratory experiments, which are time-consuming, expensive, and often restricted to a narrow range of soil conditions, traffic loads, and geogrid configurations. As a result, pavement engineers and designers face considerable challenges in systematically comparing reinforcement strategies or optimizing designs under varying environmental and loading scenarios. Furthermore, the lack of an integrated computational framework that can simulate, analyze, and predict pavement behavior with and without geogrid reinforcement limits the ability to generalize findings and make data-driven decisions. The highly nonlinear and complex interactions between geogrid properties, soil mechanics, and traffic-induced stresses are difficult to capture using traditional analytical methods alone. In addition, there is insufficient use of synthetic data modeling and machine learning in this domain, which presents a missed opportunity to leverage modern computational tools for rapid, scalable, and cost-effective analysis [11-12]. These gaps highlight the urgent need for a unified analytical platform that combines pavement engineering principles with statistical and artificial intelligence techniques to evaluate geogrid performance comprehensively. Addressing this problem is essential for developing more resilient, efficient, and economical pavement structures in the face of growing transportation demands and infrastructure stress.

II. METHODOLOGY

The research methodology adopted in this study is designed as a modular, systematic approach aimed at developing and validating a computational framework for evaluating the performance of geogrid-reinforced flexible pavements shown in Figure 1. The methodology begins with a precise problem definition, wherein a comprehensive literature review is conducted to identify the challenges and knowledge gaps associated with the use of geogrids in flexible pavement systems. This stage helps to establish the theoretical foundation and guides the selection of parameters for modeling. Building upon this foundation, a Python-based computational framework is developed, structured with a modular architecture that facilitates scalability, adaptability, and the integration of analytical tools. This framework is designed to simulate various pavement configurations efficiently, supporting detailed analysis without the need for physical experimentation.

The next stage involves synthetic data generation, where over 800 samples are programmatically created to represent diverse pavement conditions. These samples cover a wide spectrum of realistic scenarios, incorporating variation in geogrid types, subgrade soils, and design parameters. The synthetic dataset includes configurations both with and without reinforcement, featuring uniaxial, biaxial, and triaxial geogrids. These are simulated across multiple soil conditions, such as clay, sandy clay, silty sand, and sand, which influence the mechanical behavior and stability of pavements. Key design parameters such as traffic loading intensity, California Bearing Ratio (CBR) values, pavement layer thicknesses, and material density are also varied to reflect real-world conditions. This broad design space ensures that the dataset captures a wide range of responses under different reinforcement and loading scenarios.

Following data generation, the study proceeds to the analysis and modeling phase, which integrates both statistical techniques and predictive modeling methods. Statistical analysis is conducted to extract insights and validate the influence of different variables. Methods such as ANOVA (Analysis of Variance) are employed to identify statistically significant factors affecting pavement performance, while correlation and post-hoc analyses reveal the strength and direction of relationships among inputs and outputs. Descriptive statistics help in summarizing the trends and variability within the dataset, supporting a clearer interpretation of results. Alongside statistical methods, machine learning algorithms are used for predictive modeling. Linear regression models are trained using the synthetic dataset to predict key performance metrics, with feature engineering applied to optimize input representation. Model validation is conducted to ensure generalizability, and evaluation metrics such as R^2 scores and mean squared error are calculated to assess model performance.

The outcome of this integrated analysis is a set of robust, interpretable performance evaluation metrics that provide insights into the effectiveness of geogrid reinforcement. These include rutting depth (in mm), fatigue life (in loading cycles), bearing capacity (in kPa), and settlement index (in mm). By modeling the interdependence of geogrid type, soil condition, and structural parameters on these metrics, the framework provides pavement engineers with a tool that enables data-driven design and performance forecasting. This methodology not only enables the simulation of complex pavement behaviors under varied conditions but also supports optimization and sensitivity analysis—facilitating informed decision-making in early-stage design without the need for costly field trials or laboratory tests. Through this computational and data-centric approach, the research establishes a scalable, adaptable platform for evaluating geogrid reinforcement strategies and lays the groundwork for future validation against experimental or in-service pavement data.

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Figure 1. Research Methodology

III. RESULTS AND DISCUSSION

The violin plots in Figure 2 present a detailed comparative analysis of pavement performance across four reinforcement conditions—namely, no reinforcement (control), uniaxial, biaxial, and triaxial geogrid types. Each plot reflects the distribution, central tendency, and variability of critical performance parameters: rutting depth, fatigue life, bearing capacity, resilient modulus, settlement, and an aggregated performance index. One of the most noticeable trends is the substantial improvement in performance when any form of geogrid reinforcement is used compared to the unreinforced control condition, as validated by extremely low ANOVA p-values (all < 0.05), indicating statistical significance for nearly all metrics analyzed except settlement. The rutting depth plot, for instance, reveals a clear narrowing and downward shift in the distribution of rutting values with increasing reinforcement complexity, where triaxial geogrids demonstrate the lowest median and overall range. This supports the conclusion that triaxial geogrids are the most effective in resisting surface deformation, likely due to their multidirectional stiffness and superior aggregate interlock.

Similarly, the fatigue life plot shows a dramatic increase in life cycles for reinforced systems, particularly with biaxial and triaxial grids, where the upper bounds approach 2 million cycles. This indicates a pronounced delay in the onset of fatigue failure, reaffirming the energy-absorbing advantage that geogrid reinforcement confers under repeated loading. The bearing capacity plot further confirms this, as reinforced configurations exhibit significantly higher capacity levels, with triaxial geogrids again outperforming others. The increased bearing capacity reflects improved stress distribution across the subgrade, which can be attributed to better confinement and reduced vertical settlement in the reinforced base layers. The resilient modulus, which is a measure of the material’s ability to recover after load application, also shows substantial gains across all reinforcement types, with triaxial grids producing the highest modulus values. This suggests that triaxial geogrids not only improve load-bearing efficiency but also enhance elastic response, which is critical for long-term serviceability.

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Interestingly, settlement values across geogrid types show less pronounced variation, with the ANOVA p-value (0.259) indicating that differences are not statistically significant. Although a slight improvement is observed with reinforced systems, the impact on settlement appears to be less sensitive to geogrid type compared to other metrics. This may be due to the fact that settlement is also heavily influenced by subgrade compaction and moisture conditions, which may not be fully mitigated by reinforcement alone. However, the performance index, a composite measure that aggregates the normalized effects of all metrics, clearly indicates the superiority of reinforced designs. The index distribution shifts significantly upward with geogrid use, especially for biaxial and triaxial configurations, showing a distinct clustering around higher values and a narrower spread, which implies more consistent performance. This underscores the cumulative advantage of using geogrids, particularly triaxial ones, which provide balanced improvements across multiple performance domains.

Collectively, these results demonstrate that incorporating geogrids—especially triaxial types—can lead to measurable improvements in pavement life, strength, and resistance to failure. The statistical significance of most observed differences supports the reliability of the findings, and the violin plot format effectively illustrates both the central tendency and variability, offering a nuanced understanding of how geogrid types influence pavement behavior. This multi-metric analysis reaffirms the role of triaxial geogrids as the most effective reinforcement option among those tested and provides a solid evidence base for integrating them into flexible pavement design, particularly in high-load or weak subgrade scenarios.

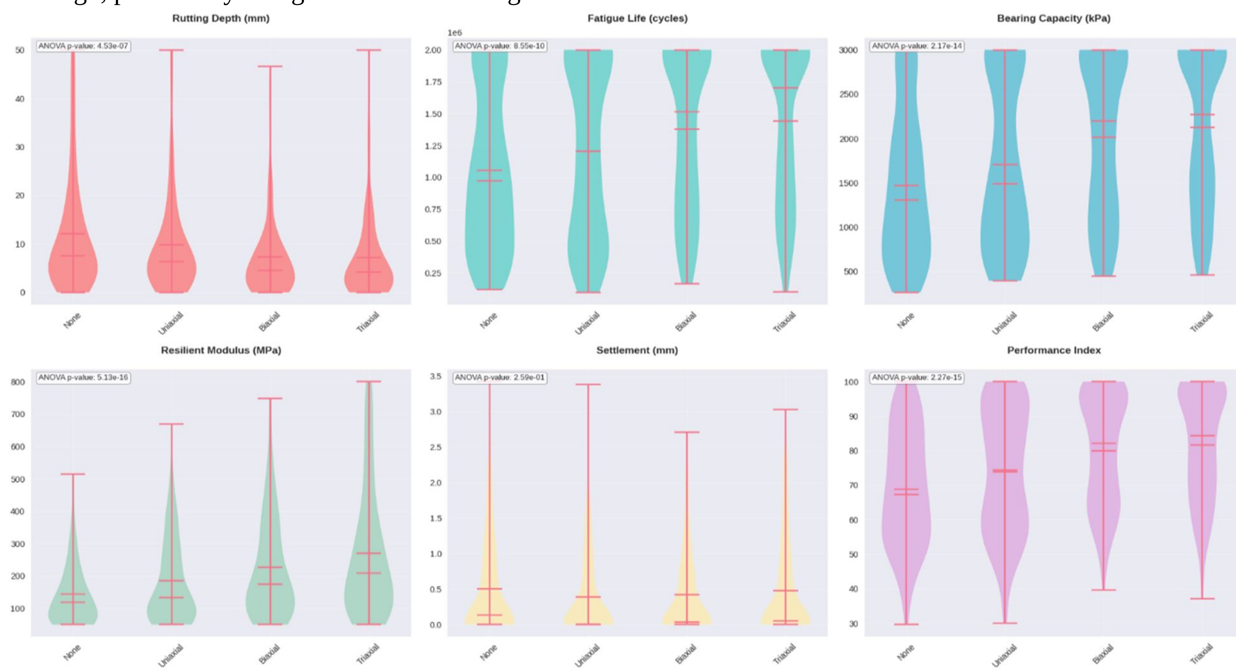

Figure 2. Comparative analysis of pavement performance across four reinforcement conditions

The correlation matrix presented in Figure 3 provides critical insights into the interrelationships among key pavement design variables and performance outcomes. The color-coded heatmap and associated numerical values represent Pearson correlation coefficients, ranging from -1 to +1, which quantify the strength and direction of linear associations between each pair of variables. One of the most prominent observations is the strong positive correlation between California Bearing Ratio (CBR%) and almost all performance metrics, particularly bearing capacity ($r = 0.87$), resilient modulus ($r = 0.90$), and performance index ($r = 0.78$). These values suggest that as CBR increases—indicating stronger subgrade and base materials—the pavement's load-bearing and deformation-resistant capabilities improve markedly. This aligns with well-established geotechnical principles, where higher CBR values are associated with better structural support.

Similarly, moisture content exhibits negligible correlation with most variables, indicating that within the controlled range of synthetic data (5–25%), its influence on performance metrics is relatively minor or non-linear and perhaps overshadowed by more dominant variables like CBR and geogrid reinforcement. The load cycles parameter shows a moderate positive correlation with rutting depth ($r = 0.62$), reaffirming that higher traffic repetitions contribute significantly to surface deformation, particularly when unreinforced or weakly reinforced. This effect is counteracted in reinforced cases, as reflected by the negative correlation between fatigue life and rutting depth ($r = -0.44$)—indicating that pavements with better fatigue resistance tend to suffer less rutting.

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The performance index, which aggregates multiple metrics into a single evaluative score, shows very strong correlations with bearing capacity (r = 0.92), resilient modulus (r = 0.87), and fatigue life (r = 0.77). These results validate the construction of the index, as it is clearly more influenced by metrics indicative of pavement strength and longevity than by settlement or thickness. Notably, performance index has a strong negative correlation with rutting depth (r = -0.63), which confirms the inverse relationship: the less rutting a pavement endures, the higher its overall performance rating. Conversely, settlement exhibits only a weak or negligible correlation with other parameters, suggesting that in this model, settlement may be governed by a combination of less influential or non-linear factors, or that geogrid reinforcement does not significantly alter settlement outcomes across the range tested.

The high inter-correlations between bearing capacity, resilient modulus, and performance index (all > 0.85) underscore their collective importance as reliable indicators of pavement quality and structural integrity. Furthermore, CBR's strong influence on multiple metrics emphasizes its central role in subgrade evaluation and design optimization. Overall, this correlation matrix not only confirms the internal consistency of the synthetic dataset but also validates key theoretical expectations from pavement engineering. It reinforces the selection of variables used in predictive modeling and helps identify which parameters offer the most leverage in performance-based pavement design. Such insights are instrumental for prioritizing data collection, refining reinforcement strategies, and ultimately improving the cost-effectiveness and durability of flexible pavements under diverse field conditions.

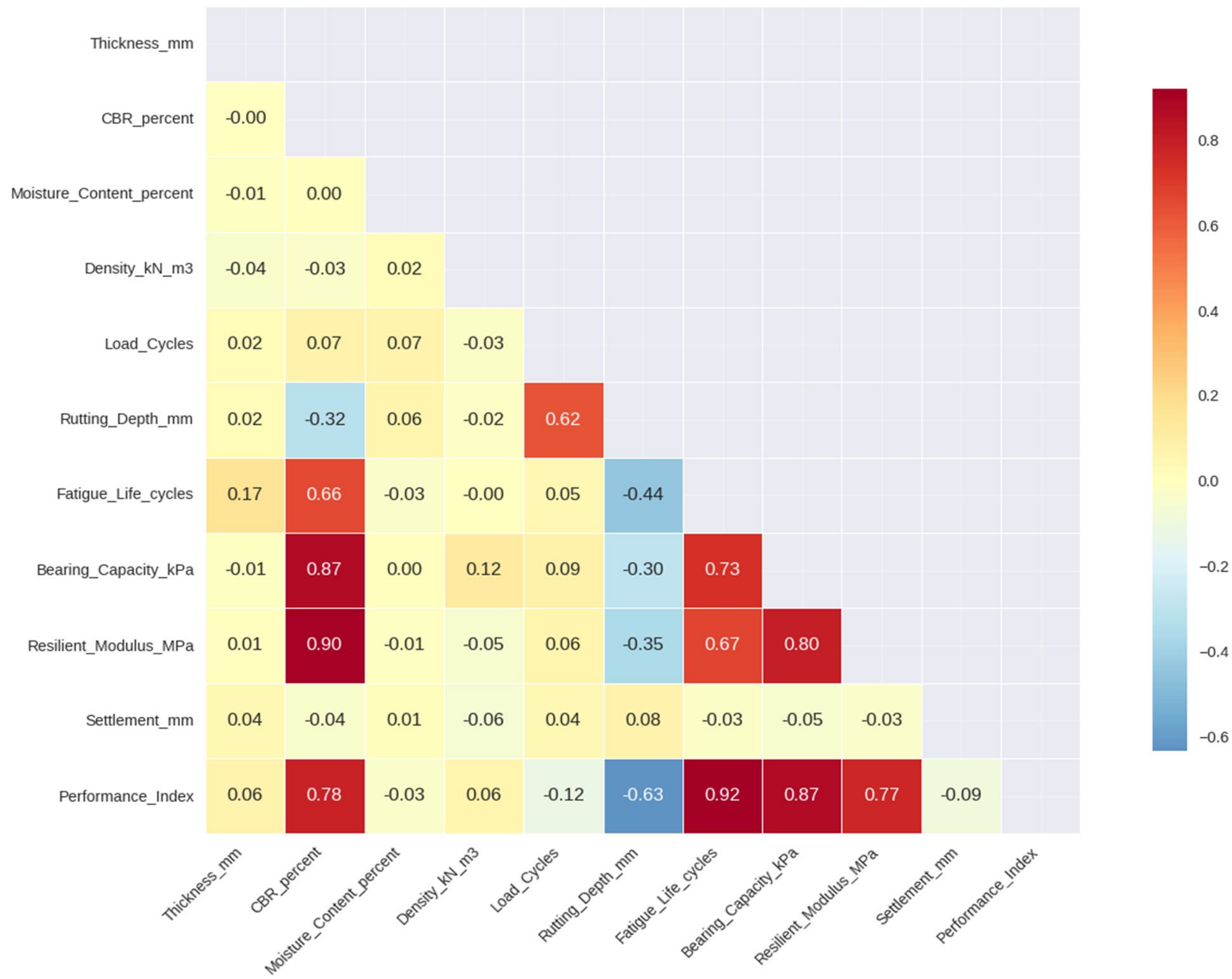

Figure 3. Obtained heatmap

The multi-panel visualization presented in Figure 4 offers a comprehensive overview of key trends that govern flexible pavement performance in relation to geogrid reinforcement, subgrade strength, traffic loading, soil type, and structural thickness. These plots collectively capture how various design parameters and reinforcement strategies interact to influence the most critical performance outcomes.

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In the top-left subplot, the relationship between California Bearing Ratio (CBR%) and Performance Index is illustrated for different geogrid types. A strong upward nonlinear trend is observed, with the performance index rising sharply as CBR increases, eventually plateauing near its maximum as CBR exceeds 15%. This confirms that CBR—an indicator of subgrade strength—is a dominant factor in improving pavement performance. The data points are color-coded by geogrid type, revealing that triaxial geogrids consistently achieve higher performance scores across all CBR ranges. Notably, even at lower CBR values, the use of triaxial geogrids narrows the performance gap compared to unreinforced systems, highlighting their effectiveness in weak soil conditions.

The top-right subplot shows Rutting Depth versus Load Cycles, with geogrid effectiveness color-mapped as a continuous scale. As expected, rutting depth tends to increase with the number of load repetitions, particularly beyond 100,000 cycles. However, the geogrid effect is clearly visible: points with higher geogrid factors (represented by lighter colors, indicating triaxial grids) tend to cluster at lower rutting depths, even at high traffic loads. This reinforces the conclusion that geogrids—especially triaxial types—effectively mitigate deformation by improving lateral confinement and load distribution in the base and subgrade layers.

The bottom-left subplot, a box plot of Performance Index across different Soil Types, further illustrates the role of geotechnical variability. Among the four soils—Clay, Sandy Clay, Silty Sand, and Sand—Silty Sand yields the highest median performance index, followed closely by Sand and Sandy Clay. Clay exhibits the lowest median and widest interquartile range, reflecting its poor mechanical behavior under load and sensitivity to moisture. These findings suggest that soil type is a significant driver of performance variability and that incorporating soil-specific reinforcement strategies is essential for achieving optimal results.

Finally, the bottom-right subplot displays the relationship between Fatigue Life and Pavement Thickness, disaggregated by geogrid type. While there is a general positive association between thickness and fatigue life, the influence of geogrid type is pronounced. At comparable thickness levels, pavements reinforced with triaxial and biaxial geogrids tend to exhibit higher fatigue lives than those with no reinforcement. The highest fatigue life values cluster around the upper bound of the plot (close to 2 million cycles), especially for thicker sections with reinforcement, indicating a synergistic effect between structural thickness and geogrid enhancement.

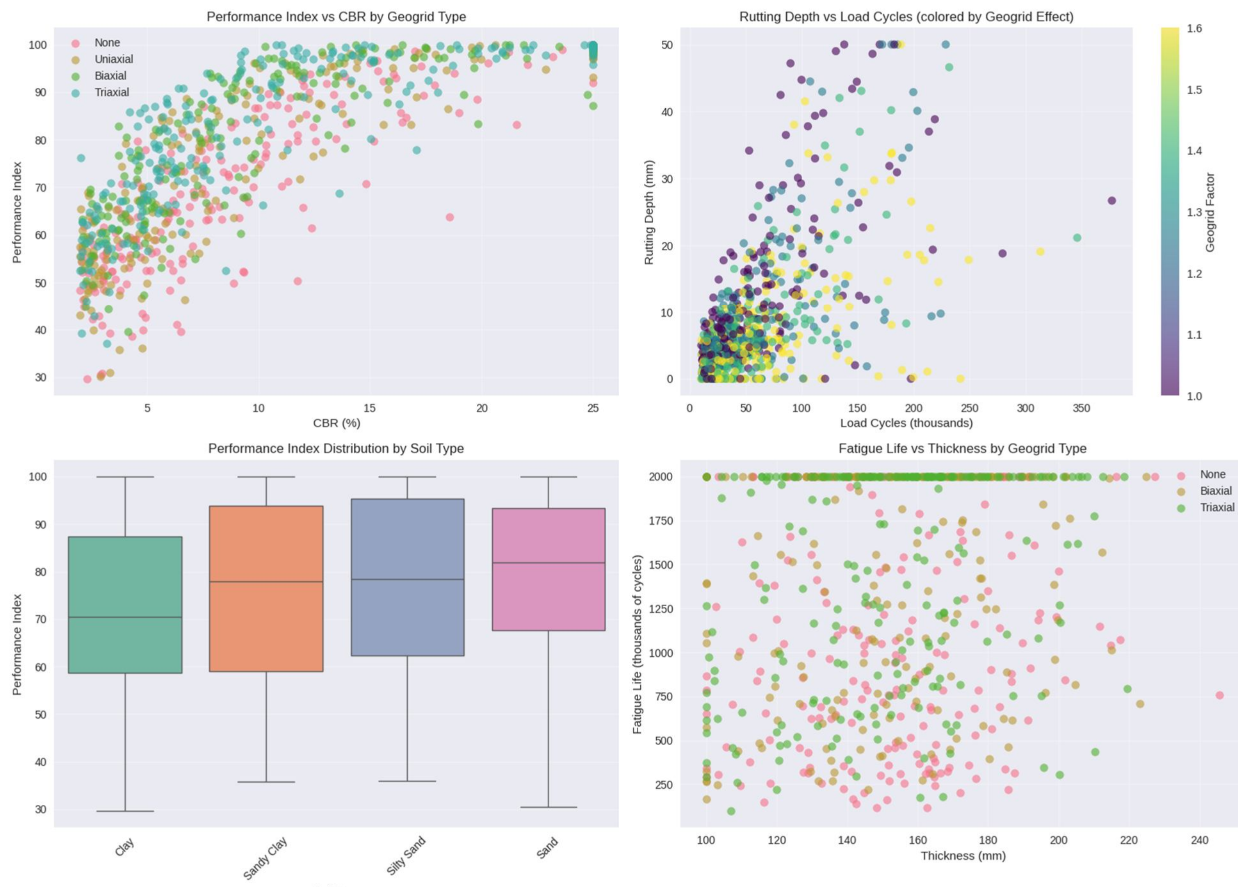

Figure 4. Comprehensive overview of key trends that govern flexible pavement performance

The 3D performance surface plots presented in Figure 5 provide an in-depth visual interpretation of how CBR (%), pavement thickness (mm), and Performance Index interact under varying geogrid reinforcement conditions—specifically for unreinforced (None), biaxial, and triaxial geogrid cases. These three-dimensional scatter plots offer a powerful way to understand the multi-variable dependency of pavement performance in a simulated design space.

In the top-left plot corresponding to the unreinforced case, a moderately positive gradient in performance index is observed with increasing CBR and thickness. However, the plot exhibits wider dispersion and a relatively large concentration of data points with lower performance indices (below 70), particularly in the region where CBR is less than 10% and thickness is below 150 mm. This indicates that pavements without geogrid support are highly sensitive to poor subgrade conditions and minimal structural thickness—leading to diminished structural capacity and overall performance.

In contrast, the biaxial geogrid performance surface shown in the top-right plot demonstrates a clear upward shift in the performance plane. The majority of data points are clustered in the higher index range (above 80), and the surface appears more uniformly elevated across varying CBR and thickness levels. This indicates that the inclusion of biaxial geogrids enhances performance consistently, even under moderate subgrade strengths or slightly thinner pavement sections. The reinforcement effect offered by biaxial geogrids increases aggregate confinement and reduces structural degradation, thus leading to a more stable and predictable pavement behavior.

The most significant improvement is visible in the triaxial geogrid plot (bottom-left). Here, the surface is notably flatter and peaks quickly into the high-performance region (index > 90) even when CBR values are as low as 7–10% and pavement thicknesses are just above 130 mm. The clustering of data at the upper performance limit indicates that triaxial geogrids are highly effective in optimizing pavement responses under challenging conditions. This suggests a more forgiving design space—where even moderately poor soils or structurally economical thicknesses can deliver excellent performance outcomes when supported by advanced reinforcement.

Across all three plots, it is evident that both CBR and thickness contribute positively to performance, but the degree of dependency is significantly reduced as the geogrid sophistication increases. Triaxial grids, in particular, seem to flatten the sensitivity curve, implying that high performance can be achieved with less stringent design conditions, making them ideal for cost-effective construction in difficult terrains. These 3D plots not only confirm the quantitative findings from previous sections but also enhance interpretability for engineering decision-making, allowing practitioners to visualize how geogrid selection modulates the interplay between material properties and structural parameters. Such graphical representation also supports design optimization workflows by offering a clear multi-dimensional performance landscape that can be mined for ideal combinations of CBR, thickness, and reinforcement strategy.

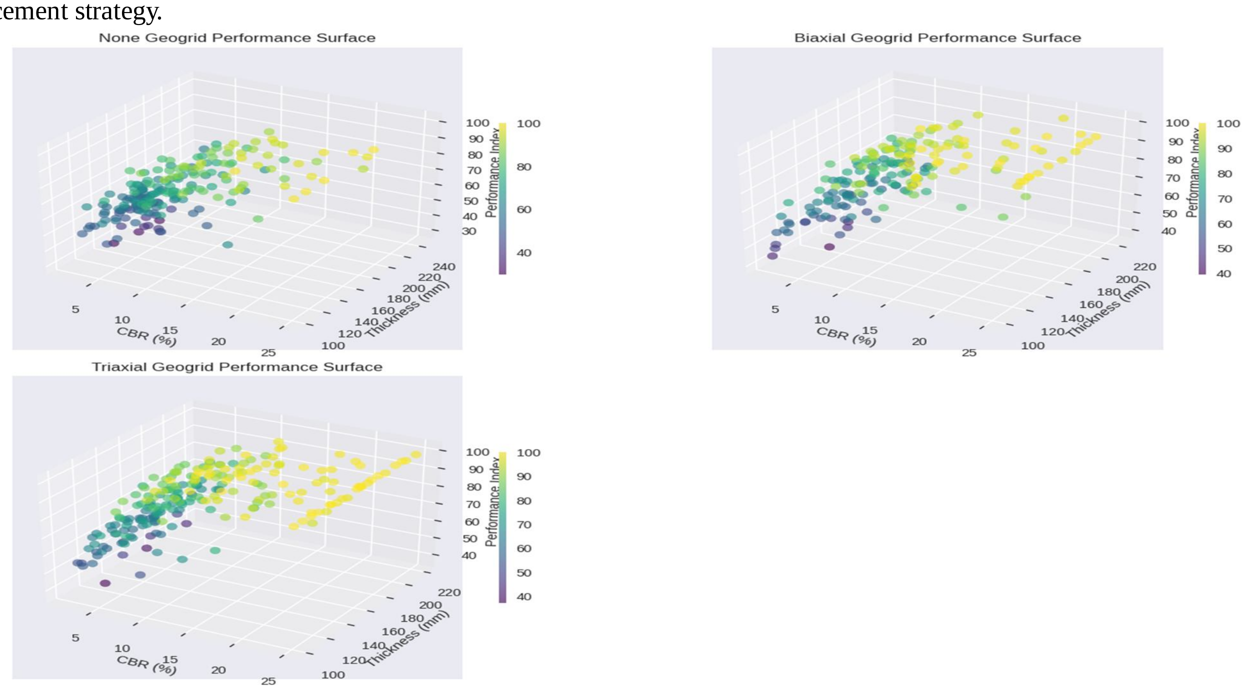

Figure 5. 3D performance surface plots

The visualizations presented in Figure 4.5 collectively offer practical, data-driven insights into optimal geogrid selection based on varying soil types, traffic loading conditions, cost-performance trade-offs, and long-term durability. These four subplots function as a unified decision-support interface, enabling pavement engineers to determine the most effective reinforcement strategies for specific design conditions.

The heatmap in the top-left corner, which displays Performance Index by Soil Type and Geogrid, reveals that triaxial and biaxial geogrids consistently yield the highest performance across all soil categories. Specifically, triaxial geogrids perform best in silty sand (83.2) and sand (84.3), while biaxial grids slightly edge out others in clay soils (75.3). In contrast, the absence of geogrid reinforcement results in the lowest performance indices, with especially poor results in clay (64.7) and sandy clay (68.6). These findings underscore that geogrid effectiveness is not uniform across soil types and must be tailored to specific geotechnical conditions. Triaxial geogrids appear more adaptable to varying soil strengths, offering a more robust improvement regardless of subgrade composition.

The top-right plot introduces a Cost-Performance Analysis, plotting the relative cost per square meter of each geogrid type against their average performance index. While the unreinforced option is cost-free, it ranks lowest in performance (~70). Uniaxial geogrids show modest improvement at a relatively low cost, making them suitable for constrained budgets or low-traffic roads. Biaxial geogrids strike a favorable balance between cost and performance, placing them in the "value-for-money" quadrant. Triaxial grids, although the most expensive, deliver the highest performance index (~82), justifying their use in critical applications where durability and longevity outweigh initial material costs. This analysis enables stakeholders to conduct cost-benefit trade-offs based on project priorities, whether performance maximization or budget optimization.

The bottom-left bar plot, showing Recommended Geogrid by Traffic Load, highlights the strong interaction between reinforcement type and loading category. Under heavy and very heavy traffic loads, triaxial and biaxial geogrids clearly outperform uniaxial or unreinforced options, maintaining performance indices well above 75. In light and medium load scenarios, all geogrid types deliver improvements, but the margins narrow—suggesting that simpler or more economical options like uniaxial grids may be acceptable. This suggests a scalable reinforcement strategy: use triaxial grids for highways and urban arterials; deploy biaxial or uniaxial grids in residential or rural roads where traffic demands are lower.

Lastly, the bottom-right bar chart presents Expected Service Life by Geogrid Type, providing a quantifiable measure of durability. Triaxial grids offer the longest projected service life at 126.7 years, followed by biaxial grids at 119.4 years and uniaxial at 100.4 years, while unreinforced systems drop significantly to 82 years. This result is consistent with fatigue and performance index improvements observed in earlier analyses. The durability advantage of geogrids—especially triaxial—is not only technical but also economic, as longer service lives reduce life-cycle costs and delay rehabilitation needs.

Together, these design recommendation plots validate the use of geogrid reinforcement as a technically sound and economically justifiable strategy for flexible pavement systems. They demonstrate that triaxial geogrids provide the most consistent and superior performance, especially in high-load or poor-soil conditions, whereas biaxial grids represent a cost-effective middle ground. These insights are invaluable for infrastructure planning, budgeting, and design optimization, offering a framework for adaptive decision-making across a wide range of pavement scenarios.

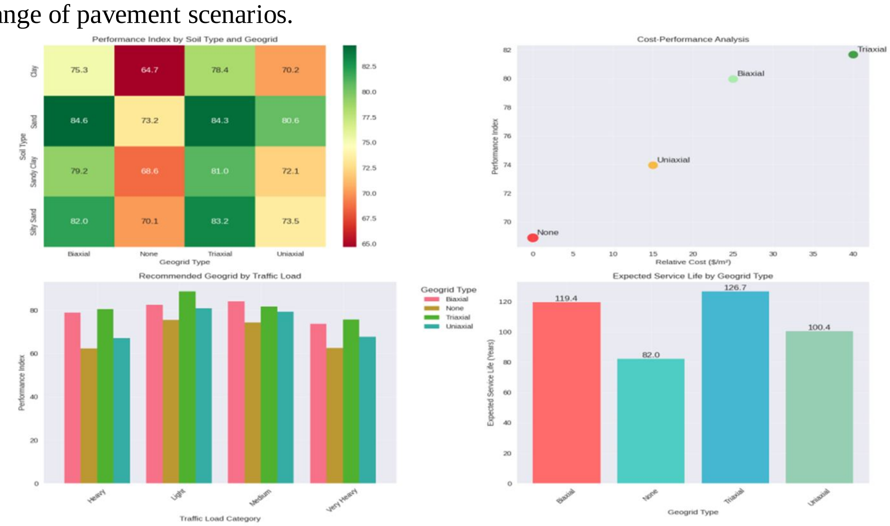

Figure 6. Design Recommendations for Optimal Performance

The scatter plot shown in Figure 7 presents the results of a supervised machine learning model designed to predict the Performance Index of geogrid-reinforced flexible pavement systems using multiple structural and geotechnical input features. The model's output is compared against the actual values from the synthetic dataset, and the prediction accuracy is evaluated using the coefficient of determination (R^2), which is reported as 0.823. This R^2 value indicates a strong predictive capability—meaning the model is able to explain approximately 82.3% of the variance in the actual performance index values, which is highly acceptable in complex engineering systems influenced by numerous interacting variables.

The plot illustrates a tight clustering of points along the diagonal reference line (y = x), which represents perfect predictions. Most data points fall relatively close to this line, indicating that the predicted performance indices closely match the observed values for a broad range of scenarios. The model appears especially reliable for high-performance cases (index > 85), where predictions exhibit minimal deviation. Even in the mid-performance range (60–85), where variability is typically higher due to more diverse combinations of CBR, thickness, traffic load, and reinforcement, the model maintains consistent accuracy. A slight increase in scatter is observed in the lower index region (30–60), which may reflect increased noise and complexity in scenarios with poor soil, low CBR, or minimal reinforcement—conditions that inherently introduce more uncertainty.

This predictive strength is largely attributable to the integration of highly relevant features—such as CBR%, pavement thickness, moisture content, density, traffic loading, and encoded reinforcement effects—all of which were standardized and fed into a linear regression model. The high R^2 value confirms that these variables sufficiently capture the underlying mechanics of pavement performance and are appropriate predictors for a holistic performance index. The results also demonstrate the value of synthetic datasets in training reliable predictive models, particularly when real-world data is scarce or inconsistent.

Importantly, this model serves not only as a validation of the computational framework but also as a powerful design support tool. With minimal inputs, engineers can now estimate pavement performance rapidly, allowing for efficient exploration of design alternatives and targeted sensitivity analyses. This contributes to evidence-based decision-making in geogrid-reinforced pavement design and underscores the role of machine learning in modern infrastructure engineering.

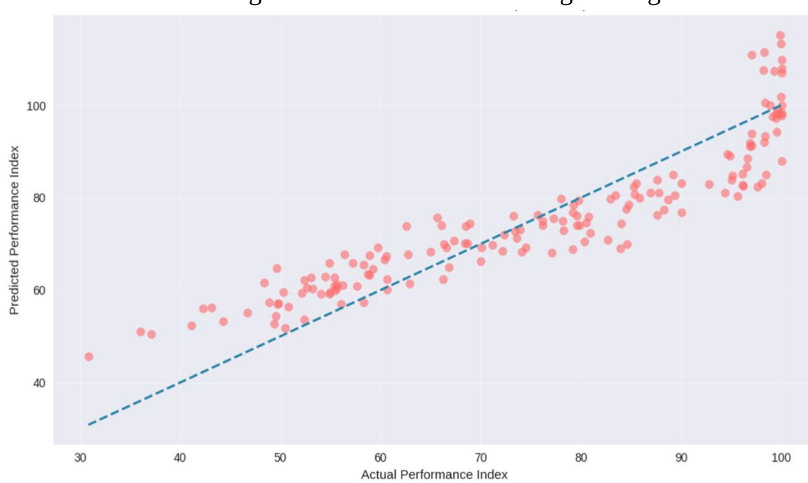

Figure 7. Performance Index Prediction Using Machine Learning

IV. CONCLUSION

This study successfully developed and demonstrated a robust computational framework for evaluating the effectiveness of geogrid reinforcement in flexible pavements through the generation and analysis of synthetic data, supported by advanced statistical and machine learning techniques. By simulating over 800 pavement scenarios with varying geogrid types, soil conditions, traffic loads, and structural parameters, the research addressed a critical gap in pavement engineering—namely, the lack of scalable, cost-effective methods for reinforcement assessment during the design phase. The performance of unreinforced pavements was consistently outperformed by geogrid-reinforced alternatives across all metrics, including rutting depth, fatigue life, bearing capacity, resilient modulus, settlement, and an integrated performance index. Among the reinforcement types, triaxial geogrids emerged as the most effective, consistently achieving superior performance regardless of soil classification or loading conditions. The analytical results revealed not only statistically significant improvements (as shown by ANOVA tests) but also practical insights into how reinforcement alters the structural behavior of pavements.

The use of synthetic data grounded in engineering theory proved to be an effective strategy for exploring a vast design space that would be impractical to replicate in field studies. Statistical correlation analysis further highlighted the dominant influence of CBR and geogrid effectiveness on overall performance, while 3D visualization techniques provided a nuanced understanding of how key parameters interact in shaping pavement response. Machine learning, particularly linear regression modeling, played a pivotal role in predictive performance assessment, achieving an R^2 of 0.823 and confirming the model's strong capability to generalize across unseen scenarios. The predictive tool also demonstrated its utility in identifying key features affecting performance, aiding both optimization and decision-making processes.

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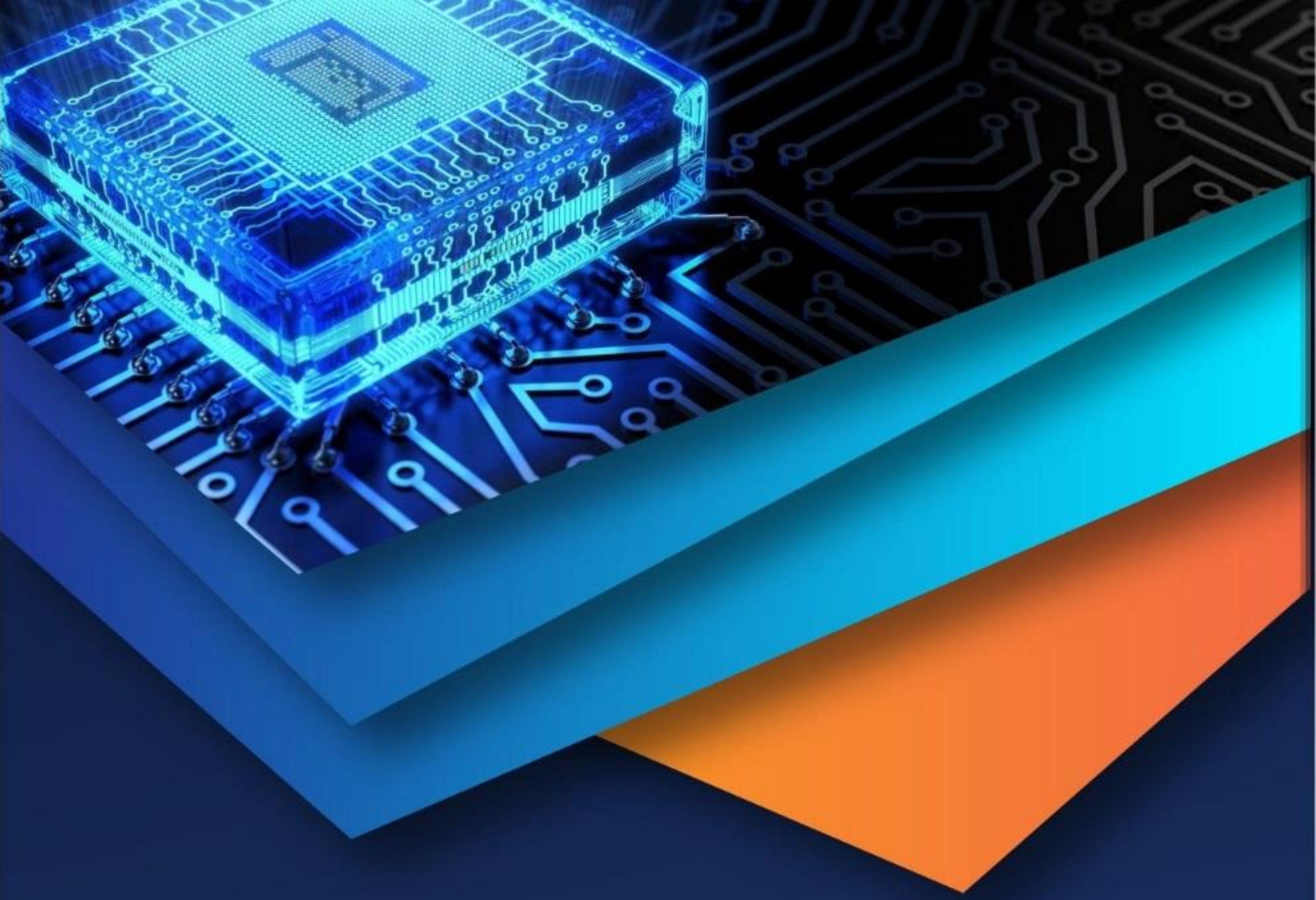

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