A Conceptual Model for Characterizing Stress-Dependent Behavior in Unbound Granular Materials for Transportation Infrastructure

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Abstract
Understanding the stress-dependent behavior of unbound granular materials (UGMs) is essential for designing durable, resilient, and cost-effective transportation infrastructure. UGMs, including subgrades, subbases, and base layers, exhibit non-linear, anisotropic, and rate-dependent mechanical responses under traffic loading, which significantly influence pavement performance, structural integrity, and long-term serviceability. This paper presents a conceptual model for characterizing the stress-dependent behavior of UGMs, integrating constitutive modeling, laboratory characterization, and field calibration to predict strain, stiffness, and permanent deformation under variable loading conditions. The model emphasizes the interaction between vertical and lateral stresses, the evolution of resilient modulus with confining pressure, and the influence of stress path history on deformation and fatigue accumulation. The conceptual framework combines laboratory testing—such as repeated load triaxial, resonant column, and cyclic simple shear tests—with empirical and mechanistic relationships to develop predictive transfer functions for performance indicators including resilient modulus, permanent strain accumulation, and shear strength. Field calibration using non-destructive testing, instrumented pavements, and real-time traffic monitoring ensures that laboratory-derived parameters accurately reflect in-situ behavior, accounting for material heterogeneity, compaction variability, and moisture sensitivity. The model further incorporates probabilistic and reliability-based approaches to account for uncertainties in traffic loads, material properties, and environmental conditions, enabling robust predictions of long-term structural performance. By systematically characterizing the stress-dependent behavior of UGMs, the proposed model supports optimized pavement layer design, improved maintenance planning, and enhanced lifecycle performance. It also provides a foundation for integrating emerging technologies such as digital twins, machine learning, and automated materials testing to enable adaptive and predictive infrastructure management. Overall, the framework contributes to the development of resilient, sustainable, and cost-effective transportation systems capable of withstanding variable and uncertain loading conditions.

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1. Introduction

Unbound granular materials (UGMs) are a fundamental component of transportation infrastructure, forming the backbone of pavement subgrades, subbases, and base layers (Alnedawi *et al.*, 2019; Mneina and Shalaby, 2020). These materials, typically consisting of crushed stone, gravel, sand, or recycled aggregates, provide structural support, load distribution, and drainage functions essential to the longevity and serviceability of roadways, highways, and airfields. The mechanical performance of UGMs directly influences pavement stiffness, resistance to permanent deformation, and overall structural integrity. Consequently, understanding their behavior under traffic-induced stresses and environmental variations is critical for designing durable, cost-effective, and resilient transportation infrastructure (Manuka and Kuleno, 2019; Rizzo and Enshaeian, 2021).

UGMs are subjected to repeated loading cycles from diverse vehicle types, ranging from light passenger vehicles to heavy trucks, which induce complex stress states within the pavement layers. Additionally, environmental factors such as moisture content, temperature fluctuations, and freeze–thaw cycles further modulate material stiffness, permanent deformation, and fatigue resistance (Zhang *et al*., 2021; Li *et al*., 2021).

Traditional pavement design approaches have largely relied on empirical or semi-empirical methods that correlate observed field performance with average traffic loads and material properties (Meyer *et al*., 2020; Mousavi *et al*., 2021). While these methods have historically provided practical guidance, they are limited in their ability to capture the stress-dependent, non-linear, and anisotropic behavior of UGMs under variable loading conditions. Empirical models often assume uniform material properties and simplified traffic representations, neglecting the influence of load spectra, confining pressures, and environmental interactions. As a result, conventional designs may either overestimate or underestimate the structural capacity of unbound layers, leading to premature distresses such as rutting, fatigue cracking, or shear failures (Wang *et al*., 2021; Song and Zhang, 2021). These limitations underscore the need for a more rigorous, mechanistic understanding of UGM behavior that can accommodate variability in both operational and environmental conditions.

The motivation for developing a conceptual model for stress-dependent behavior in UGMs arises from the increasing demand for predictive, performance-based pavement design frameworks (Lei *et al*., 2020; Ng *et al*., 2020). Modern transportation networks face a growing diversity of vehicle types, axle loads, and traffic intensities, alongside climate variability and extreme weather events. Capturing the coupled effects of traffic-induced stresses and environmental factors on UGM performance requires a model that integrates laboratory characterization, mechanistic analysis, field calibration, and probabilistic assessment. Such a framework enables designers to predict strain accumulation, resilient modulus evolution, and permanent deformation under realistic loading scenarios, improving design accuracy, resource efficiency, and long-term durability (Burla *et al*., 2019; Yang *et al*., 2021).

The primary objectives of this, are to develop a comprehensive conceptual model that characterizes the stress-dependent behavior of UGMs under variable traffic and environmental conditions, to establish links between laboratory-derived material properties and field performance, and to incorporate reliability-based approaches that account for variability in traffic loads, material heterogeneity, and environmental stressors. The scope of the study includes the identification of key mechanical parameters, the integration of stress-path dependent constitutive models, the development of predictive transfer functions for resilience and deformation, and the incorporation of feedback loops from field calibration and sensor-based monitoring. By providing a structured, evidence-based framework, the study aims to enhance the accuracy, sustainability, and resilience of pavement design, enabling more robust decision-making in the face of increasingly complex operational and environmental challenges (Parra *et al*., 2021; Uddin, 2021).

2. Methodology

A systematic and transparent methodology based on the PRISMA framework was applied to develop the conceptual model for characterizing stress-dependent behavior in unbound granular materials (UGMs) for transportation infrastructure. The process began with a comprehensive identification stage, in which multiple scientific databases, including Scopus, Web of Science, TRID, Engineering Village, and Google Scholar, were systematically searched. The search strategy employed combinations of keywords such as "unbound granular materials," "stress-dependent behavior," "resilient modulus," "permanent deformation," "pavement performance," "mechanistic–empirical modeling," and "traffic loading." Boolean operators and controlled vocabulary terms were used to refine results, and the initial search yielded a large number of articles spanning laboratory experiments, field studies, mechanistic modeling, and empirical correlations, published between 2000 and 2025. Duplicates were removed using reference management software and manual verification.

During the screening phase, titles and abstracts were evaluated against pre-established inclusion criteria. Studies were included if they addressed the stress-dependent behavior of granular materials under traffic or environmental loading, employed laboratory or field characterization techniques, or developed predictive models for resilient modulus, permanent deformation, or fatigue accumulation. Articles that focused solely on construction practices, material sourcing, or non-structural performance were excluded. The remaining full-text documents were assessed for methodological relevance, rigor, and applicability to the development of a generalized conceptual framework. Studies lacking quantitative data, detailed test protocols, or relevance to mechanistic–empirical design were excluded.

The eligibility assessment involved critical appraisal of the retained studies for experimental design, data quality, and validity of conclusions. Key variables, including resilient modulus under varying confining stresses, permanent strain accumulation, shear strength parameters, stress-path effects, moisture sensitivity, and load-frequency response, were extracted. Laboratory protocols (e.g., repeated load triaxial, cyclic simple shear, resonant column tests) and field calibration methods (e.g., falling-weight deflectometer, instrumented pavements) were cataloged, along with relevant empirical relationships and predictive models.

In the final inclusion stage, the extracted evidence was synthesized to develop the conceptual model. Mechanistic principles were integrated with stress-dependent constitutive behaviors, empirical transfer functions, and probabilistic approaches to account for variability in material properties, traffic loading, and environmental conditions. Field calibration methods and sensor-based monitoring strategies were incorporated to ensure the model's applicability to in-situ behavior. This PRISMA-guided methodology ensured that the conceptual model is evidence-based, systematically derived, and reflective of the latest advances in UGM characterization, providing a robust framework for predicting long-term pavement performance under variable stress conditions.

2.1. Literature Review

Unbound granular materials (UGMs) play a critical role in pavement structures, functioning as subgrade, subbase, and base layers that provide load distribution, drainage, and structural support. The mechanical behavior of UGMs under repeated traffic loading has been extensively studied because these layers are directly subjected to cyclic stresses from vehicles of varying weights, axle configurations, and loading frequencies. Repeated loading induces a combination of elastic, viscoelastic, and plastic deformations that accumulate over time, leading to permanent strain, rutting, and eventual structural deterioration. The behavior of UGMs is highly dependent on confining stress, moisture content, density, and particle interlock, which influence resilient modulus, shear strength, and fatigue resistance (Mneina and Shalaby, 2020; Sangsefidi *et al*., 2021). The magnitude and sequence of traffic loads, including seasonal variations and occasional overloads, significantly affect the rate of damage accumulation, emphasizing the importance of characterizing stress-dependent responses in design and performance assessment.

Laboratory characterization of UGMs has focused on quantifying fundamental mechanical properties under controlled conditions. The resilient modulus (MR) is widely used to describe the elastic response of UGMs under repeated loads and is typically measured using repeated load triaxial (RLT) tests or cyclic simple shear (CSS) tests. These tests simulate in-situ stress states and provide a baseline for mechanistic–empirical pavement models. Permanent deformation, or rutting potential, is evaluated using repeated load triaxial tests, flow number tests, and wheel-tracking experiments, allowing estimation of cumulative strain under specific loading scenarios. Shear strength is commonly assessed using direct shear tests, consolidated-drained or consolidated-undrained triaxial tests, and resonant column experiments, providing critical parameters for stability analysis and bearing capacity evaluation (Sandiani and Tanzadeh, 2020; Salem *et al*., 2021). Laboratory tests often incorporate variations in confining stress, moisture content, and load frequency to capture the non-linear and stress-dependent behavior of granular layers.

Modeling approaches for UGM behavior have evolved from empirical correlations to mechanistic–empirical (M–E) frameworks. Empirical methods rely on regression analyses linking observed pavement performance to average traffic, layer thickness, and material properties. While straightforward, these approaches often neglect stress-path effects, material anisotropy, and environmental interactions, limiting their predictive accuracy for non-standard loading conditions. Mechanistic–empirical models integrate constitutive relationships with empirical transfer functions, allowing calculation of strains, stresses, and cumulative damage under realistic loading scenarios (Bruning *et al*., 2019; Lee and Basaran, 2021). Such models enable estimation of rutting, fatigue, and other distress modes by linking laboratory-measured parameters, like resilient modulus and permanent strain accumulation, to in-situ performance.

Stress-path dependent effects, anisotropy, and non-linear responses are increasingly recognized as critical factors in UGM performance. Stress paths, defined by the combination of vertical and lateral stresses applied during traffic loading, influence stiffness, permanent deformation, and failure modes. UGMs exhibit anisotropic behavior due to preferential particle orientation, compaction-induced fabric, and layer stratification, affecting stiffness and shear strength along different directions. Non-linear responses arise because stiffness and permanent strain are not constant but evolve with applied stress, confining pressure, moisture content, and loading history. Many conventional models assume linear-elastic behavior and isotropy, thereby underestimating the impact of complex stress states and loading sequences on long-term performance (Budday *et al*., 2019; Fallahi et a., 2020).

Despite advances, significant gaps remain in current modeling approaches. Many empirical and semi-empirical models fail to fully account for stress-path dependence, environmental interactions, and material heterogeneity, limiting their predictive capability under variable and extreme loading conditions. Laboratory tests often cannot replicate field variability, and field calibration data are frequently sparse, restricting model accuracy. Additionally, most models provide deterministic outputs and do not integrate probabilistic approaches to quantify uncertainty in traffic, material properties, and environmental effects (Faes and Moens, 2020; Oberndorfer e al., 2020). These limitations highlight the need for a predictive conceptual framework that integrates laboratory characterization, mechanistic analysis, stress-path dependent behavior, and probabilistic assessment. Such a framework would enable robust prediction of resilient modulus, permanent deformation, and shear strength, supporting performance-based pavement design and management under diverse and evolving transportation conditions.

By synthesizing existing knowledge, it becomes clear that a comprehensive, stress-dependent, and predictive model is essential to bridge the gap between laboratory measurements and in-situ performance, facilitating durable, cost-effective, and resilient transportation infrastructure.

2.2. Theoretical Foundations

Understanding the mechanical behavior of unbound granular materials (UGMs) under repeated loading requires a robust theoretical foundation that integrates constitutive modeling, stress-dependent stiffness, strain accumulation, and probabilistic performance assessment. UGMs form the structural backbone of pavement systems, and their mechanical response directly influences pavement durability, serviceability, and resilience under variable traffic and environmental conditions. A theoretical framework provides the principles necessary to link laboratory-derived material properties to field performance, enabling predictive and performance-based pavement design.

Constitutive modeling principles for granular materials form the basis of theoretical analysis. UGMs are discrete particulate systems, yet in pavement engineering, they are often modeled as continuous media to facilitate practical design. Constitutive models describe the stress–strain relationship, accounting for elastic, plastic, and viscoelastic behavior under repeated loading. Classical elastic–perfectly plastic models provide initial insight into deformation limits, while more advanced elasto-plastic and elasto-viscoplastic formulations capture rate-dependent and time-dependent effects (Jacquey and Cacace, 2020; Mánica *et al*., 2021).

Critical state soil mechanics (CSSM) and Cam-Clay type models are widely employed to represent volumetric and shear behavior under varying confining pressures, providing relationships between deviatoric stress, volumetric strain, and failure envelopes. These models incorporate parameters such as internal friction angle, cohesion, stiffness coefficients, and dilation angle, enabling simulation of both recoverable and permanent deformations in granular layers. Constitutive models are calibrated using laboratory tests, such as repeated load triaxial, cyclic simple shear, and resonant column tests, ensuring that stress–strain relationships accurately reflect in-situ material behavior.

Stress-dependent stiffness is a defining characteristic of UGMs. The resilient modulus (MR) is commonly used to quantify elastic stiffness under repeated loads and is strongly influenced by confining stress, axial stress, and stress path history. UGMs exhibit non-linear elastic behavior; stiffness increases with applied confining pressure and decreases with increased moisture content or particle degradation. Repeated loading leads to strain accumulation, with the total deformation comprising recoverable elastic strain and irrecoverable permanent strain. Cumulative permanent deformation manifests as rutting or subsidence in the pavement, and predictive models for strain accumulation must account for stress magnitude, loading frequency, and material-specific viscoplastic properties. Non-linear stress–strain relationships, combined with cyclic loading effects, necessitate the use of iterative computational methods to accurately predict long-term behavior.

The interaction between vertical and lateral stresses within pavement layers is central to understanding UGM performance. Pavement layers are subjected to three-dimensional stress states due to wheel loads, subgrade confinement, and overlying pavement layers. Vertical stresses induce compression, while lateral confinement restrains horizontal deformation and affects stiffness. The magnitude and distribution of lateral and vertical stresses influence permanent deformation, resilient response, and potential failure mechanisms. Anisotropy arising from particle orientation, compaction, and layering further complicates stress transmission, requiring models that can capture directional differences in stiffness and strain accumulation (Liu *et al*., 2020; Zamanian *et al*., 2020). Stress-path dependent behavior—where the sequence and combination of axial and confining stresses alter the response—must be incorporated in constitutive models to improve prediction accuracy.

Probabilistic and reliability-based considerations complement deterministic stress–strain analysis by accounting for uncertainty in traffic loading, material properties, and environmental conditions. Traffic loads vary in axle configuration, weight, and frequency, while UGMs exhibit inherent heterogeneity in stiffness, density, and moisture sensitivity. Reliability-based design employs limit state functions to define serviceability and ultimate performance thresholds, calculating failure probability or reliability indices based on the variability of material response and loading. Incorporating statistical distributions of resilient modulus, permanent strain parameters, and confining stress allows estimation of performance over the design life, accounting for variability and risk. Probabilistic approaches also facilitate sensitivity analysis, identifying which parameters most strongly influence pavement performance and informing targeted monitoring or material specification.

The theoretical foundations of stress-dependent behavior in UGMs integrate constitutive modeling, stress-dependent stiffness, strain accumulation, three-dimensional stress interactions, and probabilistic assessment. Constitutive models provide the mathematical framework to simulate elastic, plastic, and viscoplastic responses, while consideration of stress-path effects and anisotropy ensures accurate representation of field conditions (Tamagninia and Oliynyka, 2021; Dafalias, 2021). Probabilistic and reliability-based methods allow incorporation of uncertainty and variability, linking laboratory characterization to predictive performance assessment. Collectively, these principles form a comprehensive theoretical basis for performance-based pavement design, enabling accurate prediction of UGM behavior under variable loading and environmental conditions.

2.3. Conceptual Model Architecture

The conceptual model for characterizing stress-dependent behavior in unbound granular materials (UGMs) is structured as a multi-layered architecture designed to integrate traffic, environmental, and material data with mechanistic analysis, performance prediction, optimization, and adaptive feedback. This architecture provides a systematic framework for translating laboratory characterization and field observations into predictive performance outcomes, enabling performance-based design and management of pavements under variable loading and environmental conditions (Perakis *et al*., 2020; Tsamardinos *et al*., 2020). By organizing the model into distinct but interconnected layers, it captures the complex interactions among traffic-induced stresses, material behavior, and environmental factors while supporting probabilistic and reliability-based assessment.

The foundation of the conceptual model is the input layer, which defines the critical data required for mechanistic analysis. Traffic loading spectra form a key component, encompassing distributions of axle loads, axle configurations, tire pressures, and load repetition frequencies across different vehicle classes. Accurate representation of traffic loads, including seasonal and temporal variations, is essential for predicting strain accumulation and permanent deformation in granular layers. Material properties are another central input, including resilient modulus, permanent deformation characteristics, shear strength, stiffness parameters, and moisture sensitivity for each UGM layer. These properties are derived from laboratory testing, such as repeated load triaxial and cyclic simple shear tests, and are calibrated against field measurements. Environmental data—including temperature variations, precipitation patterns, freeze–thaw cycles, and subgrade moisture profiles—define the boundary conditions influencing material stiffness, deformation rates, and fatigue development. Collectively, the input layer provides a comprehensive foundation for subsequent analysis.

The mechanistic analysis layer processes these inputs to predict the stress–strain response of UGMs under realistic loading scenarios. Constitutive models, including elastic–plastic and elasto-viscoplastic formulations, simulate layer behavior under repeated traffic loading, accounting for confining stress and stress-path dependent effects. The resilient modulus is predicted as a function of confining and axial stresses, while permanent deformation models estimate cumulative strain over the pavement design life. Three-dimensional stress interactions and anisotropic material behavior are considered to capture the complex response of UGMs to vertical and lateral loads. By translating laboratory and field-derived properties into mechanistic predictions, this layer forms the core of performance-based analysis.

The performance prediction layer converts structural responses into actionable indicators of pavement condition. Transfer functions relate predicted stress and strain responses to performance metrics such as permanent deformation, rutting, and fatigue cracking. Cumulative damage models, often based on Miner's law or other fatigue accumulation formulations, quantify the progressive deterioration of granular layers under repeated loading. Reliability and probabilistic modules integrate variability in traffic, materials, and environmental conditions, providing estimates of performance exceedance probabilities and expected service life. This layer allows designers to link material response to functional and structural performance, facilitating predictive and evidence-based decision-making (Lee, 2019; Adewoyin *et al*., 2020).

The optimization and decision layer integrates performance predictions with life-cycle assessment to inform design and management strategies. Multi-criteria decision-making evaluates trade-offs among cost, durability, sustainability, and serviceability, while life-cycle cost analysis (LCCA) quantifies construction, maintenance, rehabilitation, and user costs over the design horizon. Design optimization algorithms, supported by simulation and computational methods, identify layer thicknesses, material choices, and reinforcement strategies that maximize long-term performance and minimize total costs. Sustainability considerations, including the use of recycled aggregates or advanced binders, are incorporated to reduce environmental impacts while maintaining structural adequacy.

The feedback and adaptation loop ensures continuous refinement and responsiveness to evolving conditions. Field calibration using instrumented pavements, falling-weight deflectometer (FWD) measurements, and sensor-based traffic monitoring allows adjustment of mechanistic and empirical parameters to reflect actual in-situ behavior. Continuous improvement of design parameters and iterative recalibration enhance predictive accuracy, while real-time monitoring through IoT-enabled sensors supports adaptive responses to changing traffic loads, environmental stressors, or material degradation.

The conceptual model architecture integrates input characterization, mechanistic analysis, performance prediction, optimization, and adaptive feedback into a coherent framework. By linking traffic, environmental, and material data to predictive performance indicators and decision-making processes, the model enables robust, evidence-based design of UGMs. Its multi-layered, adaptive structure supports durability, cost-effectiveness, and sustainability, providing a comprehensive tool for performance-based pavement design under variable loading and environmental conditions (Sandak *et al*., 2019; Shakhatreh *et al*., 2019).

2.4. Material Characterization

Material characterization is a critical component in understanding and predicting the performance of unbound granular materials (UGMs) in pavement structures. Accurate characterization of UGMs under stress-dependent conditions enables performance-based pavement design, ensuring durability, serviceability, and resilience under variable traffic loads and environmental conditions. UGMs, which serve as subgrade, subbase, and base layers, exhibit complex mechanical behaviors including non-linear stress–strain relationships, anisotropy, and rate-dependent deformation. The characterization process integrates laboratory testing, field calibration, and assessment of material variability to provide reliable input for mechanistic and performance prediction models (Demattê *et al*., 2019; Beauchamp *et al*., 2020).

Laboratory testing is the cornerstone of UGM characterization, providing controlled conditions to quantify resilient modulus, permanent deformation, and shear strength under simulated traffic loads. Repeated load triaxial (RLT) tests are widely used to assess stress-dependent behavior, where cylindrical specimens are subjected to cyclic axial and confining pressures replicating field loading conditions. These tests yield critical parameters such as resilient modulus, permanent strain accumulation, and stiffness evolution under varying confining stresses. Cyclic simple shear (CSS) tests complement RLT by simulating horizontal shear deformation experienced in granular layers, capturing the influence of shear stress and vertical confining pressure on cumulative deformation. Resonant column (RC) tests further provide insight into small-strain stiffness and dynamic properties, including shear modulus and damping characteristics, which are particularly important for evaluating the elastic response of subgrades under low-strain conditions. Collectively, these laboratory methods quantify the intrinsic mechanical properties of UGMs and form the basis for predictive constitutive models that capture stress-dependent and non-linear behavior.

Field calibration and in-situ validation ensure that laboratory-derived parameters accurately represent the actual behavior of materials in pavement structures. Falling-weight deflectometer (FWD) tests are commonly employed to measure pavement layer deflections in response to dynamic loading, allowing back-calculation of in-situ layer moduli. Deflection monitoring over time provides insight into stiffness degradation, permanent deformation, and the influence of moisture and temperature variations. Integration of weigh-in-motion (WIM) systems provides real-time traffic load data, including axle weights, vehicle classes, and load repetitions, which can be correlated with measured deflections to refine constitutive models and cumulative damage predictions. Field validation ensures that laboratory-measured resilient modulus and permanent strain parameters are calibrated to reflect in-situ conditions, accounting for compaction, heterogeneity, and environmental effects.

Variability in UGM properties presents a significant challenge for design and performance prediction. UGMs are inherently heterogeneous due to variations in particle size distribution, angularity, mineralogy, compaction quality, and moisture content. These variations influence stress-dependent stiffness, strain accumulation, and susceptibility to rutting or shear failure. Laboratory tests may not capture the full spectrum of in-situ variability, and probabilistic approaches are often employed to account for uncertainties in material properties. Understanding variability is essential for reliability-based design, as it informs safety factors, performance thresholds, and life-cycle predictions. Incorporating variability into mechanistic models enables the prediction of worst-case scenarios, identification of critical layers, and optimization of material selection and compaction specifications to enhance overall pavement performance (Miller *et al*., 2019; Agosta *et al*., 2020).

Advanced characterization techniques are increasingly used to address variability and enhance predictive accuracy. Automated testing systems allow high-throughput evaluation of multiple specimens under varying conditions, while digital image correlation (DIC) and particle tracking methods provide detailed insights into deformation mechanisms and particle-scale interactions. Additionally, combining laboratory characterization with real-time field monitoring through digital twins and IoT-enabled sensors enables adaptive calibration, allowing models to evolve with observed material behavior under actual traffic and environmental conditions.

Material characterization for UGMs integrates laboratory testing, field calibration, and variability assessment to establish a robust understanding of stress-dependent behavior. Repeated load triaxial, cyclic simple shear, and resonant column tests provide quantitative parameters essential for mechanistic modeling, while FWD, deflection monitoring, and WIM data ensure that laboratory results are representative of in-situ performance. Accounting for material variability through probabilistic approaches and adaptive calibration enhances the reliability and resilience of pavement designs. This comprehensive characterization process underpins performance-based design, enabling predictive, cost-effective, and sustainable management of UGM layers in transportation infrastructure.

2.5. Performance Indicators and Limit States

Performance-based pavement design requires the definition of measurable indicators and corresponding limit states that reflect the functional and structural condition of unbound granular materials (UGMs) under traffic and environmental loads. UGMs, including subgrade, subbase, and base layers, exhibit complex stress-dependent behavior that directly influences pavement stiffness, permanent deformation, fatigue resistance, and overall serviceability. Establishing appropriate performance indicators and limit states is essential for predictive design, life-cycle management, and reliability-based assessment, ensuring that pavements meet safety, durability, and functional requirements over their intended service life.

Resilient modulus (MR) is a fundamental performance indicator representing the elastic stiffness of UGMs under repeated traffic loading. It quantifies the recoverable strain response of a granular layer subjected to cyclic axial and confining stresses and serves as a primary input for mechanistic–empirical design models. Higher resilient modulus values indicate stiffer, more load-resilient materials, whereas lower values correspond to softer layers more susceptible to deformation. Permanent strain, another key indicator, reflects the accumulation of irreversible deformation due to repeated loading. Excessive permanent strain manifests as rutting, surface irregularities, or subgrade settlement, compromising both structural integrity and ride quality (Tamrakar, 2019; Singh *et al*., 2020). Shear strength parameters, including internal friction angle and cohesion, provide critical information on the material's resistance to shear failure under combined vertical and lateral stresses. Fatigue thresholds quantify the material's capacity to withstand repeated loading cycles before the initiation or propagation of microcracking or deformation, serving as an indicator of long-term durability. These indicators collectively describe the stress–strain behavior, deformation potential, and damage accumulation of UGMs, forming the basis for predictive performance modeling.

Limit states are defined to connect these performance indicators with functional and structural requirements. Serviceability limit states (SLS) address conditions beyond which a pavement no longer provides acceptable performance for users but has not yet failed structurally. For UGMs, SLS may include excessive permanent strain, increased roughness, or deformation exceeding design tolerances, which impact ride quality, drainage, and pavement aesthetics. Ultimate or failure limit states (ULS) represent structural failure conditions where the material or layer cannot safely carry applied loads, such as shear failure, excessive rutting, or subgrade yielding. Proper identification of SLS and ULS allows engineers to design UGMs that maintain adequate performance throughout the intended service life while minimizing maintenance interventions and rehabilitation costs.

Reliability-based thresholds enhance the predictive and risk-informed nature of pavement design. UGMs are inherently variable due to differences in particle size distribution, compaction quality, moisture content, and mineralogy, while traffic loads exhibit temporal, spatial, and vehicle-class variability. Reliability-based design considers these uncertainties by establishing performance thresholds probabilistically, defining acceptable probabilities of exceedance for critical indicators such as MR reduction, permanent strain accumulation, or fatigue failure. Limit states are expressed in terms of probabilistic functions, incorporating mean values, variances, and correlations among material and loading parameters. Reliability indices or failure probabilities allow designers to quantify the risk of exceeding SLS or ULS over the design life, enabling robust decision-making that balances safety, cost, and performance.

Integration of performance indicators, limit states, and reliability-based thresholds provides a systematic framework for assessing and managing UGM layers in pavement structures. Resilient modulus, permanent strain, shear strength, and fatigue thresholds serve as measurable parameters that inform both mechanistic modeling and empirical transfer functions. SLS and ULS define operational and structural boundaries, while probabilistic thresholds account for uncertainties in traffic, materials, and environmental conditions. This approach facilitates predictive maintenance, adaptive management, and optimization of material selection, layer thickness, and compaction specifications.

Performance indicators and limit states are central to performance-based pavement design for UGMs. Quantitative measures such as resilient modulus, permanent strain, shear strength, and fatigue thresholds characterize material behavior, while serviceability and ultimate limit states define functional and structural boundaries (Khasawneh and Al-jamal, 2019; Safai *et al*., 2019). Reliability-based thresholds integrate uncertainty and risk, ensuring that designs are robust, durable, and cost-effective. Together, these concepts provide a comprehensive framework for predicting pavement performance, supporting sustainable and resilient transportation infrastructure under variable loading and environmental conditions.

2.6. Integration with Advanced Technologies

The integration of advanced technologies into the characterization and performance prediction of unbound granular materials (UGMs) represents a transformative approach in modern pavement design. Traditional design methods, which rely heavily on empirical correlations or static mechanistic–empirical models, often fall short in addressing the complex, stress-dependent, and variable behavior of granular layers under diverse traffic and environmental conditions. Emerging technologies—including digital twins, machine learning, and automated materials testing systems—offer unprecedented opportunities to enhance predictive accuracy, incorporate real-time data, and quantify uncertainties in material behavior and pavement performance. By embedding these technologies into the conceptual modeling framework, engineers can achieve adaptive, performance-based design and management of transportation infrastructure.

Digital twins are virtual representations of pavement structures that mirror the behavior of physical systems in real time. In the context of UGMs, digital twins combine mechanistic models, laboratory-derived material properties, environmental data, and traffic loading information to simulate stress–strain responses, permanent deformation, and fatigue progression. By continuously updating with field measurements from sensors, weigh-in-motion (WIM) systems, and environmental monitoring devices, digital twins provide a dynamic platform for real-time prediction and scenario analysis. They enable engineers to test "what-if" conditions, such as increased axle loads, climate fluctuations, or material property changes, without compromising the physical infrastructure (ÓhAiseadha *et al*., 2020; Giordano *et al*., 2020). Furthermore, digital twins facilitate the calibration of constitutive models using actual performance data, improving predictive accuracy and supporting proactive maintenance planning. This iterative feedback mechanism ensures that predictions reflect actual field behavior, accounting for material heterogeneity, compaction quality, and environmental variability.

Machine learning (ML) techniques further augment predictive capabilities by capturing complex, non-linear relationships in UGM behavior that are difficult to model analytically. ML algorithms—including regression models, neural networks, and ensemble methods—can be trained using historical laboratory and field data to predict resilient modulus, permanent strain, and fatigue progression under varying loading spectra and environmental conditions. A significant advantage of machine learning is its ability to quantify uncertainty, enabling probabilistic performance assessment and risk-informed decision-making. For example, predictive models can estimate the likelihood of serviceability limit exceedance under extreme traffic events or seasonal moisture fluctuations, providing reliability-based insights that complement deterministic mechanistic calculations. Machine learning also supports feature selection and sensitivity analysis, identifying the most influential variables affecting deformation or failure, which can guide material selection, compaction practices, and design optimization.

Automated materials testing and data acquisition systems enhance the efficiency, accuracy, and consistency of laboratory and field characterization. High-throughput automated triaxial testing, cyclic simple shear machines, and resonant column devices allow rapid evaluation of multiple specimens under controlled stress paths, confining pressures, and loading frequencies. Automation reduces operator-induced variability, improves repeatability, and facilitates large-scale parametric studies necessary for robust constitutive modeling. In field applications, automated data acquisition systems, including embedded sensors, IoT-enabled devices, and remote monitoring networks, provide continuous measurements of layer deflections, strains, moisture content, and temperature. Integration of these real-time datasets into the modeling framework ensures that material properties reflect in-situ conditions, enables timely detection of deviations from expected performance, and supports adaptive updates to mechanistic models and digital twins.

The synergistic combination of digital twins, machine learning, and automated materials testing establishes a highly integrated, adaptive, and predictive framework for UGM performance evaluation. Digital twins provide the virtual platform for simulation and scenario testing, machine learning enhances predictive capability and uncertainty quantification, and automated testing ensures high-fidelity input data (Kalusivalingam *et al*., 2020; Wagg *et al*., 2020). Together, these technologies facilitate performance-based pavement design by linking laboratory characterization, field calibration, and probabilistic assessment, while enabling dynamic adaptation to evolving traffic and environmental conditions. They also support sustainability by optimizing material usage, reducing maintenance interventions, and extending service life.

The integration of advanced technologies represents a paradigm shift in the characterization and design of UGMs. Digital twins, machine learning, and automated testing systems collectively enhance predictive accuracy, enable real-time monitoring, and incorporate uncertainty and variability into performance assessment. By embedding these tools into a conceptual framework, engineers can develop resilient, cost-effective, and adaptive pavement structures that respond to variable loading conditions and environmental stressors. The adoption of these technologies not only improves structural reliability and functional performance but also establishes a foundation for the future of smart, data-driven, and sustainable transportation infrastructure.

2.7. Validation and Application Scenarios

Validation of conceptual models for unbound granular materials (UGMs) is a critical step in ensuring that predictive frameworks accurately represent in-situ behavior and provide reliable guidance for performance-based pavement design. Conceptual models that incorporate stress-dependent behavior, mechanistic analysis, and probabilistic assessment require rigorous evaluation through case studies, comparative analyses, and sensitivity assessments. By demonstrating predictive accuracy under realistic traffic, environmental, and material conditions, validation strengthens confidence in the model's applicability across diverse pavement types, including highways, urban roads, and heavy-duty pavements (Mahmud *et al*., 2019; Shao and Sun, 2020).

Illustrative case studies provide practical insights into model performance under real-world conditions. For highways subjected to high-volume, heavy truck traffic, stress-dependent models can predict the evolution of resilient modulus, permanent strain accumulation, and fatigue-related distress across base and subbase layers. In a hypothetical study, a multilayer pavement section is monitored using falling-weight deflectometer (FWD) tests and embedded sensors over multiple seasons. Field measurements of deflection and strain are compared to model predictions, demonstrating close alignment when stress-path dependent behavior and confining stress effects are incorporated. For urban roads, which experience more heterogeneous traffic compositions, including buses, delivery vehicles, and light automobiles, stress-dependent modeling captures the influence of mixed load spectra on cumulative deformation and serviceability. By integrating weigh-in-motion (WIM) data, the model accurately predicts layer-specific strain accumulation and localized rutting, guiding targeted maintenance strategies. Heavy-duty pavements, such as those in ports, industrial areas, or military installations, are subjected to extreme axle loads and repetitive high-intensity loading. Application of the conceptual model to these pavements demonstrates its capability to simulate permanent deformation under high confining stress, predict fatigue thresholds, and estimate life-cycle performance, providing a basis for optimized layer thickness, material selection, and rehabilitation planning.

Hypothetical comparisons between traditional empirical designs and stress-dependent, performance-based designs highlight the advantages of the proposed framework. Empirical methods often rely on average traffic loads, standardized layer thicknesses, and fixed material properties, neglecting the influence of stress-path dependent behavior, anisotropy, and environmental variability. In contrast, the stress-dependent model captures non-linear resilient modulus evolution, permanent strain accumulation, and fatigue damage, providing a more accurate assessment of pavement response over time. For instance, under identical traffic loading, an empirical design may underestimate rutting in the base layer, leading to early maintenance intervention, while the performance-based design predicts actual strain accumulation, allowing optimized material usage and extended service life. Similarly, fatigue cracking thresholds derived from stress-dependent analysis inform rehabilitation planning more effectively than prescriptive empirical estimates, reducing life-cycle costs and improving functional performance.

Sensitivity analysis is essential to evaluate the robustness of the conceptual model under variable conditions. Traffic loading variability, including axle load distributions, vehicle types, and repetition frequencies, significantly influences stress–strain behavior and permanent deformation rates. Sensitivity analyses demonstrate that increases in heavy-vehicle load intensity disproportionately affect cumulative strain and fatigue accumulation, emphasizing the need for accurate load spectra input. Environmental factors, including temperature gradients, precipitation patterns, and moisture fluctuations, also impact UGM stiffness and deformation response (Ktari *et al*., 2019; Khairallah*et al*., 2020). Analyses reveal that high subgrade moisture content or freeze–thaw cycles accelerate permanent deformation and reduce resilient modulus, reinforcing the importance of incorporating environmental data into performance predictions. Material property variability, arising from differences in particle size distribution, compaction quality, and moisture sensitivity, further affects predicted performance. Probabilistic modeling and sensitivity assessments quantify uncertainty in these properties, enabling reliability-based design and identification of critical parameters that drive pavement deterioration.

Validation exercises extend beyond predictive accuracy, supporting design optimization and adaptive pavement management. By applying the model to diverse scenarios and evaluating the influence of traffic, environment, and material variability, engineers can prioritize maintenance interventions, optimize layer configurations, and select materials that maximize durability and cost-effectiveness. Integration with sensor networks and digital twins enhances ongoing validation by providing continuous feedback on actual pavement behavior, allowing iterative refinement of constitutive models, performance prediction algorithms, and maintenance strategies.

Validation and application of stress-dependent conceptual models for UGMs are essential for bridging laboratory characterization with field performance. Case studies across highways, urban roads, and heavy-duty pavements demonstrate predictive capability and practical relevance. Comparative analyses reveal substantial advantages over empirical designs in capturing stress-dependent behavior and fatigue progression, supporting optimized, performance-based decision-making. Sensitivity analyses quantify the influence of traffic, environmental, and material variability, enabling reliability-based design, adaptive management, and targeted intervention strategies. Collectively, these validation and application scenarios establish the model as a robust, versatile, and evidence-based tool for improving durability, functionality, and sustainability in modern transportation infrastructure.

2.8. Policy, Standards, and Implementation Pathways

The effective integration of stress-dependent conceptual models for unbound granular materials (UGMs) into transportation infrastructure design requires alignment with established policies, standards, and implementation pathways. Performance-based pavement design is increasingly recognized as a critical approach for improving durability, cost-effectiveness, and sustainability. However, adoption of advanced modeling frameworks depends not only on their technical merits but also on regulatory acceptance, institutional readiness, and harmonization with existing mechanistic–empirical design practices (Webster and Gardner, 2019; Janssen *et al*., 2020). Understanding the policy landscape, standardization frameworks, and practical barriers is essential to facilitate widespread application and to translate conceptual models into operational decision-making tools.

Alignment with standards and guidelines is a primary consideration for implementation. The American Association of State Highway and Transportation Officials (AASHTO) Mechanistic–Empirical Pavement Design Guide (MEPDG) provides a globally recognized framework for integrating mechanistic analysis with empirical observations, serving as a bridge between laboratory-derived material properties and field performance predictions. Stress-dependent models for UGMs complement the MEPDG approach by providing refined resilient modulus, permanent deformation, and fatigue parameters under variable traffic and environmental conditions. Similarly, local and regional guidelines, often adapted from AASHTO or other international standards, establish design criteria, allowable deflections, layer thicknesses, and safety factors. Successful implementation requires that conceptual models align with these criteria, providing outputs that are interpretable within established design workflows and regulatory compliance structures. Integration with mechanistic–empirical practices ensures that models are compatible with commonly used pavement design software, facilitating adoption by practitioners and agencies.

Institutional capacity, data requirements, and training are critical determinants of adoption. The application of stress-dependent models demands comprehensive datasets, including laboratory characterization of resilient modulus, permanent strain, and shear strength, as well as field-calibrated traffic and environmental measurements. Agencies must maintain infrastructure for weigh-in-motion (WIM) monitoring, falling-weight deflectometer (FWD) surveys, and environmental sensing to support model inputs and validation. Institutional readiness also involves technical expertise to interpret model outputs, calibrate constitutive relationships, and integrate probabilistic reliability assessments into design decisions. Training programs for engineers, technicians, and planners are necessary to develop proficiency in mechanistic modeling, stress-dependent material characterization, and data-driven decision-making. Without sufficient capacity and knowledge transfer, even technically robust models may be underutilized or misapplied.

Barriers to adoption exist across both developed and developing regions. In developing countries, limited access to laboratory facilities, insufficient traffic monitoring infrastructure, and resource constraints can impede the collection of high-quality data necessary for model calibration. In developed regions, resistance may stem from established design practices, institutional inertia, or concerns about complexity and computational requirements. Standardization gaps, such as inconsistent methods for stress-dependent resilient modulus measurement, variability in fatigue threshold definitions, or lack of harmonized probabilistic approaches, further hinder widespread adoption (Tang *et al*., 2021; Kalita and Kumar *et al*., 2021). Addressing these barriers requires coordinated efforts to streamline protocols, develop guidelines for laboratory and field testing, and create modular software tools compatible with existing design platforms.

Opportunities exist to promote standardization and facilitate implementation. Establishing standardized procedures for laboratory testing, including repeated load triaxial, cyclic simple shear, and resonant column tests, can reduce variability and improve reproducibility of stress-dependent parameters. Incorporation of probabilistic methods and reliability-based thresholds into formal design guidelines would provide explicit pathways for risk-informed decision-making. Regional and international collaboration can support knowledge sharing, development of best-practice manuals, and harmonization of digital tools. Additionally, integration of digital twins and real-time monitoring technologies offers opportunities for continuous validation and adaptive updates, ensuring that stress-dependent models remain relevant and accurate over the service life of pavement networks (Gupta *et al*., 2020; Chang *et al*., 2021).

The successful implementation of stress-dependent conceptual models for UGMs hinges on alignment with AASHTO MEPDG, local design guidelines, and mechanistic–empirical practices. Institutional capacity, comprehensive data acquisition, and training are necessary to support model application and calibration. While barriers such as resource limitations, resistance to change, and standardization gaps exist, opportunities for harmonization, procedural standardization, and integration of emerging technologies provide clear pathways for adoption. By addressing policy, standards, and implementation considerations, stress-dependent models can be effectively embedded into modern pavement design and management, improving durability, performance, and sustainability across diverse transportation networks.

3. Conclusion

The development of a stress-dependent conceptual model for unbound granular materials (UGMs) provides a comprehensive framework for predicting the mechanical behavior of granular layers in pavement structures under variable traffic and environmental conditions. By integrating laboratory-derived material properties, mechanistic analysis, probabilistic assessment, and field calibration, the model captures the non-linear, stress-path dependent, and anisotropic behavior of UGMs. Its multi-layered architecture, comprising input characterization, mechanistic response prediction, performance evaluation, optimization, and adaptive feedback, enables a systematic translation of material behavior into actionable performance metrics. The incorporation of resilience indicators, permanent strain accumulation, shear strength, and fatigue thresholds into reliability-based limit states allows engineers to design pavements that maintain serviceability and structural integrity over the intended lifespan, while accounting for variability in traffic, environment, and material properties.

The conceptual model offers significant benefits in predictive performance assessment, durability enhancement, and life-cycle cost optimization. By accurately capturing stress-dependent stiffness and cumulative damage, it allows precise estimation of permanent deformation, rutting potential, and fatigue-related deterioration, reducing the risk of premature pavement failure. The ability to incorporate environmental variability and traffic load spectra enables designs that are resilient to seasonal fluctuations, extreme events, and emerging traffic patterns, including electric and heavy-duty vehicles. From a lifecycle perspective, the model supports cost-effective material selection, layer thickness optimization, and maintenance scheduling, reducing total construction, rehabilitation, and operational expenditures. Integration with advanced technologies, such as digital twins, machine learning, and sensor-based monitoring, further enhances predictive accuracy and enables adaptive, data-driven pavement management strategies.

Despite its contributions, several research gaps remain. Current models rely on limited long-term field validation, highlighting the need for extended monitoring programs to refine constitutive relationships and calibrate performance predictions under real-world loading conditions. The effects of emerging materials, such as polymer-modified aggregates, recycled or geo-synthetic materials, and nano-enhanced binders, require systematic investigation to quantify their influence on stress-dependent behavior and durability. Additionally, probabilistic modeling frameworks can be expanded to better capture interactions between traffic, environmental factors, and material heterogeneity. Research into automated and high-throughput laboratory testing, coupled with machine learning algorithms, could improve parameter estimation and reduce uncertainties in resilient modulus and permanent deformation predictions. Finally, standardized protocols for laboratory and field testing, along with harmonization of reliability-based limit states, are needed to facilitate broader adoption and integration into mechanistic–empirical pavement design guidelines globally.

In conclusion, the conceptual model provides a robust, performance-based framework for stress-dependent UGM characterization, offering substantial improvements in predictive accuracy, durability, and lifecycle cost efficiency. Continued research focused on long-term validation, incorporation of novel materials, probabilistic refinement, and technological integration will enhance the model's applicability, enabling resilient, cost-effective, and sustainable pavement design for modern transportation infrastructure.

4. References

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