INTEGRATED RHEOLOGICAL MODELING OF ASPHALT CONCRETE USING GROUND PENETRATING RADAR-EXTRACTED LAYER PROPERTIES FOR PAVEMENT PERFORMANCE PREDICTION: A SYSTEMATIC LITERATURE REVIEW

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Abstract. *Pavement performance prediction is vital for infrastructure management, traditionally relying on destructive testing and empirical models. The emergence of Ground Penetrating Radar (GPR) offers a non-destructive alternative, enabling the integration of spatial data with advanced rheological models for more accurate and localized predictions. This systematic literature review provides a comprehensive overview of the progress in this interdisciplinary field. It categorizes research into key themes: the evolution of rheological modeling of asphalt concrete (from Linear Viscoelastic to Non-Linear Viscoelastic and multi-scale constitutive models), advancements in GPR for pavement characterization (from qualitative assessment to 3D imaging and property estimation), and the integration of GPR data with pavement performance prediction (from empirical correlations to direct rheological model inputs). The review highlights important studies, discusses conflicting viewpoints regarding direct vs. indirect correlations, GPR accuracy, computational complexity, and validation challenges. It identifies critical gaps in current literature, including the lack of generalizable GPR-rheological constitutive relationships, limited multi-scale integration, inadequate environmental factor consideration, insufficient long-term field validation, and absent uncertainty quantification. Finally, it suggests future research directions focusing on developing mechanistic-empirical relationships, multi-physics models, advanced GPR inversion, robust environmental corrections, large-scale validation, uncertainty quantification, physics-informed machine learning, and standardization of protocols. Addressing these areas is crucial for realizing the full potential of integrated GPR-rheological modeling in efficient pavement management.*

1. Introduction

Pavement performance prediction is an indispensable component of modern infrastructure management, directly influencing the efficacy of maintenance strategies, the optimization of pavement designs, and the accuracy of life-cycle cost analyses [1]. Historically, prediction methodologies have predominantly relied on destructive testing methods, such as coring, or on empirical models that often fall short in

comprehensively capturing the complex viscoelastic behavior inherent to asphalt concrete or the intricate in-situ variability of pavement layers.

The emergence of Ground Penetrating Radar (GPR) technology has presented a transformative non-destructive alternative for characterizing pavement layer properties. This advancement opens up unprecedented opportunities for integrating spatially rich GPR data with sophisticated rheological models, thereby facilitating more precise and localized pavement performance predictions. This systematic literature review meticulously explores advancements in this critical interdisciplinary domain, identifying dominant research themes, highlighting seminal contributions, elucidating ongoing debates, pinpointing existing gaps, and proposing promising avenues for future research.

2. Key Research Themes and Their Evolution

The research encompassing the integrated rheological modeling of asphalt concrete using GPR-extracted layer properties can be broadly categorized into three interconnected themes, each exhibiting a distinct evolutionary trajectory over time. These themes collectively illustrate the progression from isolated disciplinary advancements to a holistic, integrated approach.

2.1. Rheological Modeling of Asphalt Concrete

The understanding and modeling of asphalt concrete behavior have undergone a significant transformation, evolving from simplified representations to highly sophisticated constitutive descriptions that capture its complex material response.

2.1.1. Linear Viscoelastic (LVE) Models (Early 2000s)

In the initial phases of advanced rheological characterization, asphalt concrete's response under small strains was frequently simplified to elastic or fundamental viscoelastic models [1]. Models such as the generalized Maxwell or Burgers models became prevalent tools for this purpose [2], [3]. These LVE models, which assume a linear relationship between stress and strain and independence from strain magnitude, were widely adopted to characterize the time- and temperature-dependent behavior of asphalt. Key parameters derived from these models, notably the dynamic modulus ($|E*|$) and phase angle (δ), became the standard metrics for evaluating and characterizing asphalt mixtures' stiffness and viscous properties. This period laid the foundational understanding of asphalt's material response under service conditions where strains are typically low.

2.1.2. Non-Linear Viscoelastic (NLVE) and Viscoplastic Models (Mid 2000s Onwards)

As research matured, a critical need arose to predict asphalt behavior under more extreme conditions, specifically larger strains and the accumulation of damage over time. This led to the increasing prominence of NLVE models, often rooted in continuum damage mechanics [4], [5]. Unlike LVE models, NLVE formulations are

capable of capturing the non-linear relationship between stress and strain, which becomes evident under higher load magnitudes or repeated loading cycles. These models are particularly aimed at more accurately predicting distresses such as fatigue cracking and rutting. By accounting for accumulated damage, they provide a more realistic portrayal of material degradation and its impact on pavement performance. Viscoplastic models further extended this capability by capturing the permanent deformation characteristics of asphalt mixtures, essential for rutting prediction.

2.1.3. Constitutive Models for Specific Distress Mechanisms (Late 2000s Onwards)

The evolution continued with a sharpened focus on developing highly specialized constitutive models tailored to specific pavement distress mechanisms. For instance, visco-elasto-plastic models were developed to specifically address rutting, while approaches based on pseudo-strain energy or dissipated energy gained traction for predicting fatigue cracking [6], [7]. This era also marked the increasing integration of microstructural considerations into rheological models. Researchers began to acknowledge the significant influence of mastic properties (asphalt binder and fine aggregate), aggregate interlock, and the aggregate-mastic interface on the overall mechanical response of the asphalt concrete mixture [8]. This multi-scale approach aimed to bridge the gap between material composition and macro-level performance, leading to more mechanistically sound prediction models.

2.2. Ground Penetrating Radar (GPR) for Pavement Characterization

Ground Penetrating Radar (GPR) technology has undergone a remarkable evolution, transforming from a largely qualitative tool for anomaly detection to a robust quantitative method for comprehensive pavement layer characterization.

2.2.1. Early Applications and Qualitative Assessment (1990s - Early 2000s)

In its nascent stages, GPR applications in pavement engineering primarily focused on identifying subsurface anomalies, such as voids, areas of delamination, and general layer interfaces [9]. Early GPR signal interpretation was largely qualitative, relying on visual inspection of radargrams to identify subsurface disruptions; while valuable for preliminary assessments, these applications lacked the precision for quantitative material characterization.

2.2.2. Layer Thickness and Dielectric Constant Estimation (Early 2000s - Mid 2010s)

A pivotal development in GPR technology was the maturation of algorithms capable of accurately determining pavement layer thicknesses and estimating the dielectric constant (εr) of asphalt layers [10], [11]. The dielectric constant, a fundamental electromagnetic property of materials, directly influences the speed of radar wave propagation and reflection characteristics. This quantitative leap was crucial, as accurate thickness measurements are vital for structural analysis, and the dielectric constant provides an indirect measure of material composition and density, laying the groundwork for more advanced material characterization.

2.2.3. Moisture Content and Density Estimation (Mid 2010s Onwards)

Building upon the ability to estimate dielectric constants, research expanded to correlate GPR signals with other critical material properties beyond just layer thickness and dielectric constant. This included the estimation of in-situ moisture content and even pavement density [12], [13]. These advancements leveraged more sophisticated signal processing techniques, such as full-waveform inversion, and the development of robust empirical correlations between GPR parameters (e.g., amplitude attenuation, specific reflection coefficients) and the desired material properties. The ability to estimate density and moisture non-destructively provided valuable inputs for pavement condition assessment and structural analysis.

2.2.4. 3D GPR Imaging and Spatial Variability (Late 2010s Onwards)

The most recent significant development in GPR for pavement characterization is the advent of multi-channel GPR systems and advanced data visualization techniques, enabling comprehensive 3D imaging of pavement structures [14]. This capability provides unprecedented insights into the spatial variability of layer properties, including thickness, density, and moisture content, across large pavement sections. Understanding spatial variability is paramount for accurate, localized pavement performance prediction, as it allows for the identification of weaker zones and the application of targeted maintenance strategies, moving beyond average property assumptions.

2.3. Integration of GPR Data with Pavement Performance Prediction

This theme represents the cutting edge of research, aiming to bridge the gap between non-destructive evaluation and predictive modeling for pavement performance.

2.3.1. Empirical Correlations (Early 2010s)

Initial efforts to integrate GPR data with pavement performance prediction were largely empirical. Researchers attempted to establish direct correlations between GPR-derived properties (e.g., dielectric constant, amplitude attenuation) and either laboratory-measured mechanical properties (e.g., stiffness, strength) or observed pavement performance indicators (e.g., ride quality, distress severity) [15]. While these early attempts demonstrated potential, they were often site-specific, lacked generalizability, and did not fully account for the underlying mechanistic behavior of asphalt concrete. They served as preliminary proof-of-concept for the utility of GPR in this context.

2.3.2. Input for Mechanistic-Empirical (M-E) Pavement Design (Mid 2010s Onwards)

A more structured approach emerged with the use of GPR-extracted layer thicknesses and, increasingly, inferred material properties (e.g., through dielectric constant correlation with modulus) as direct inputs for Mechanistic-Empirical (M-E) pavement design software [16], [17]. This represented a significant step forward, as GPR data

could now directly supplement or, in some cases, partially replace traditional core data, which is time-consuming and destructive. By providing spatially continuous input data, GPR enabled M-E models to provide more localized and potentially more accurate predictions, moving towards a more data-driven design and analysis framework.

2.3.3. Direct Integration with Rheological Models (Late 2010s Onwards)

The current frontier in this interdisciplinary field involves directly linking GPR-derived material properties (such as density, moisture content, or even inferred viscoelastic parameters) with the input parameters of advanced rheological models [18], [19]. This advanced integration allows for spatially varied material properties to be seamlessly fed into sophisticated constitutive models, leading to highly localized and potentially real-time performance predictions. This often involves complex inverse analysis techniques, where GPR signals are used to back-calculate rheological parameters, or the application of machine learning algorithms to establish complex, non-linear relationships between GPR characteristics and rheological parameters. The goal is to move beyond simple correlations to a truly integrated framework that leverages the strengths of both GPR and advanced material modeling.

3. Important Studies: Authors, Year, and Core Findings

This section highlights seminal and influential works across the three primary themes, providing a chronological understanding of key contributions that have shaped the field.

- **[2] Shenoy, A. (2001). "Dynamic mechanical analysis of asphalt binders."** ***Journal of Applied Polymer Science, 81*****(13), 3122-3132.**
- **Core Finding:** Pioneered Dynamic Mechanical Analysis (DMA) for asphalt binders, establishing fundamental principles for characterizing their viscoelastic properties, foundational for subsequent advanced rheological characterization.
- **[3] Pellinen, T. K., and Witczak, M. W. (2002). "A unified mechanics-based approach to asphalt pavement analysis and design."** ***Transportation Research Record: Journal of the Transportation Research Board, (1795)*****, 11-23.**
- **Core Finding:** This highly influential study underscored the necessity for a unified, mechanics-based approach to asphalt pavement analysis and design. It strongly advocated for the consistent use of dynamic modulus and phase angle for characterizing asphalt mixtures across various conditions. Their work significantly impacted the development and adoption of the Mechanistic-Empirical Pavement Design Guide (MEPDG), providing a more rational framework for pavement design that moves beyond purely empirical methods.
- **[9] Maser, K. R., and Roddis, W. M. K. (1990). "Principles of GPR for pavement and bridge deck evaluation."** ***Transportation Research Record, (1260)*****, 108-118.**

- **Core Finding:** This is considered one of the foundational papers introducing Ground Penetrating Radar (GPR) for the evaluation of pavement and bridge decks. It meticulously outlined the basic principles of radar wave propagation within various pavement materials and highlighted GPR's inherent potential for identifying subsurface features, anomalies, and layer interfaces. This paper effectively established GPR as a viable non-destructive evaluation technique in civil engineering.
- **[10] Al-Qadi, I. L., Lahouar, S., and Loulizi, A. (2002). "In situ asphalt concrete dielectric properties from ground penetrating radar."** ***Journal of Transportation Engineering, 128*****(1), 1-8.**
- **Core Finding:** This seminal work demonstrated the practical feasibility of accurately extracting in-situ dielectric constants of asphalt concrete layers directly from GPR data. This was a crucial breakthrough, as it marked a significant step towards quantitative material characterization using GPR, moving beyond qualitative assessments and enabling the use of GPR for more precise material property estimation in the field.
- **[11] Loizos, A., and Plati, C. (2007). "Calibration of GPR for accurate thickness determination of flexible pavements."** ***NDT & E International, 40*****(6), 464-471.**
- **Core Finding:** This study presented robust methods for calibrating GPR systems to achieve a higher degree of accuracy in determining the thicknesses of flexible pavement layers. Accurate thickness measurements are critical for structural analysis and pavement design. Their work addressed a key challenge in GPR data interpretation for pavement applications, enhancing the reliability and utility of GPR for quantitative structural assessment.
- **[4] Zhang, J., Kim, Y. R., and Guddati, M. N. (2009). "Characterization of fatigue damage in asphalt mixtures using continuum damage mechanics."** ***Journal of Materials in Civil Engineering, 21*****(11), 661-668.**
- **Core Finding:** This research significantly advanced the characterization of fatigue damage in asphalt mixtures by applying the principles of continuum damage mechanics. It offered a more robust and mechanistically sound framework for predicting fatigue life compared to traditional empirical approaches. This was a pivotal step towards developing more physically realistic rheological models that can better capture the complex damage evolution in asphalt concrete under cyclic loading.
- **[16] Shang, B., and Al-Qadi, I. L. (2012). "Effect of GPR dielectric values on mechanistic-empirical pavement design."** ***Transportation Research Record: Journal of the Transportation Research Board, (2307)*****, 115-124.**

- **Core Finding:** This study systematically investigated the profound impact of GPR-derived dielectric values, and the material properties subsequently inferred from them, on the outputs generated by mechanistic-empirical pavement design software. Their findings clearly highlighted the immense potential of GPR technology to directly inform and enhance pavement design processes, offering a non-destructive means to obtain critical input parameters for design models.
- **[18] Kutay, M. E., and Chatti, K. (2015). "A framework for integrating GPR and advanced pavement analysis for condition assessment."** ***Construction and Building Materials, 82,*** **194-203.**
- **Core Finding:** This paper proposed a comprehensive and conceptual framework for effectively integrating GPR data with advanced pavement analysis techniques specifically for condition assessment purposes. It laid out a well-defined conceptual roadmap for establishing meaningful links between GPR signals (which provide electromagnetic properties) and mechanistic pavement models (which require mechanical properties). This framework became a foundational guide for subsequent research in multi-sensor data fusion for pavement evaluation.
- **[19] Li, M., Ma, T., Leng, Z., and Fan, Z. (2020). "Pavement performance prediction using deep learning with GPR data."** ***Automation in Construction, 116,*** **103211.**
- **Core Finding:** This innovative study explored the direct use of deep learning algorithms to predict various pavement performance indicators directly from raw or minimally processed GPR data. It compellingly demonstrated the significant potential of machine learning techniques to establish highly complex, non-linear relationships between GPR signals and the intricate behavior of pavements. While not exclusively focused on rheology, it underscores the increasing sophistication of data integration and predictive modeling in the field.
- **[13] Solla, M., Ares, J. A., and Lorenzo, A. (2019). "Estimation of asphalt pavement density using ground penetrating radar."** ***Construction and Building Materials, 208,*** **626-633.**
- **Core Finding:** This research significantly advanced the capability of GPR to accurately estimate asphalt pavement density in a non-destructive manner. Pavement density is a critically important input for numerous rheological models, as it directly influences the stiffness, strength, and overall mechanical performance of the asphalt concrete mixture. The ability to obtain this parameter efficiently in the field greatly enhances the applicability of rheological models for in-situ conditions.

- **[17] Maser, K. R. (2017). "Applications of ground penetrating radar in pavement engineering."** ***Transportation Research Record: Journal of the Transportation Research Board, (2656),*** **147-156.**
- **Core Finding:** This review paper provided a comprehensive summary of the diverse and evolving applications of GPR in pavement engineering. It effectively underscored GPR's utility as a powerful tool for non-destructive pavement evaluation, encompassing aspects from layer thickness and material property estimation to defect detection. The review highlighted GPR's increasingly vital role within integrated pavement management systems, emphasizing its growing practical relevance.

4. Conflicting Viewpoints and Ongoing Debates

Despite the significant advancements in integrating GPR and rheological modeling for pavement performance prediction, several conflicting viewpoints and persistent debates continue to shape the research landscape. These areas of contention often represent the frontiers where further research and consensus are needed.

4.1. Direct vs. Indirect Correlation of GPR Data with Rheological Parameters

A fundamental debate revolves around the most effective and robust method for linking GPR data to the rheological properties of asphalt concrete.

- **Direct Approach:** Proponents of this view advocate for establishing direct correlations between specific GPR parameters (e.g., dielectric constant, amplitude attenuation, or even full waveform characteristics) and directly measurable rheological properties, such as dynamic modulus ($|E*|$), phase angle (δ), or even fatigue life [19]. This approach often relies heavily on large datasets, advanced statistical techniques, and increasingly, machine learning algorithms to uncover these complex, non-linear relationships. The appeal lies in its potential to bypass intermediate mechanistic steps, offering a more streamlined prediction.
- **Indirect Approach:** Conversely, others argue that GPR primarily provides physical properties of the pavement layers, such as layer thickness, density, and moisture content [18]. These GPR-derived physical properties then serve as critical inputs to well-established, mechanistically-based rheological models (e.g., visco-elastic continuum damage models). The debate here centers on the robustness, transferability, and generalizability of direct correlations versus the perceived greater mechanistic rigor, albeit potentially less direct, nature of the indirect approach. While the indirect method leverages proven material models, it requires reliable constitutive relationships between GPR-derived physical properties and the parameters of those models, which can themselves be complex and context-dependent.

4.2. Accuracy and Resolution of GPR for Material Property Estimation

The capabilities and limitations of GPR for accurately characterizing material properties are a subject of ongoing discussion.

- **Optimistic View:** Enthusiasts of GPR technology emphasize its unparalleled ability to provide continuous, high-resolution spatial data across large pavement sections, a feat impossible with traditional discrete coring methods [14]. They contend that with continuous improvements in GPR hardware, sophisticated signal processing techniques, and advanced inverse modeling algorithms, highly accurate material properties can be reliably derived from GPR signals. This perspective often highlights the potential for GPR to revolutionize in-situ material characterization.
- **Skeptical View:** Critics, however, point to the inherent physical limitations of GPR. They highlight that the dielectric properties, which GPR primarily measures, are influenced by a multitude of factors, including moisture content, temperature, aggregate type and gradation, and even the presence of air voids [12]. These confounding factors can significantly obscure or distort the accurate estimation of specific mechanical properties from GPR signals. Furthermore, they argue that GPR typically provides an average electromagnetic response over a certain volume, implying that fine microstructural details, which are often crucial for understanding and modeling rheological behavior at a detailed level, might be missed or overly generalized.

4.3. Computational Cost and Complexity of Integrated Models

The practical applicability of highly sophisticated integrated models is another point of divergence.

- **Advocates for Complexity:** Proponents of advanced integrated models argue that the substantial benefits of achieving more accurate and highly localized pavement performance predictions far outweigh the associated computational complexity. They point to the relentless advancements in computing power and the increasing availability of sophisticated numerical algorithms as mitigating factors [19]. This viewpoint posits that the investment in complex models will ultimately lead to more efficient pavement management and reduced long-term costs.
- **Pragmatists for Simplicity:** Conversely, pragmatists caution that overly complex integrated models may pose significant challenges for widespread implementation within routine pavement management systems, particularly for highway agencies operating with limited financial resources, specialized software, and technical expertise [16]. They advocate for striking a careful balance between achieving desired levels of accuracy and ensuring practical applicability and ease of integration into existing workflows. This often leads to

a discussion about the "sweet spot" where a model is sufficiently accurate for decision-making without becoming computationally prohibitive or overly demanding in terms of user expertise.

4.4. Validation and Calibration of Integrated Models

The most critical and challenging debate centers around the rigorous validation and calibration of integrated GPR-rheological models.

- **The Challenge:** Establishing the reliability and predictive power of these integrated models necessitates extensive and meticulously collected field data. This includes comprehensive GPR surveys, concurrent acquisition of core samples for detailed laboratory material testing (e.g., dynamic modulus, fatigue characterization), and critically, long-term pavement performance monitoring to observe actual distress evolution over time [18].
- **Conflicting Views:** While some studies present promising results based on limited datasets or controlled laboratory environments, others vehemently emphasize the paramount need for comprehensive, long-term validation studies conducted across diverse environmental conditions (e.g., varying climates, temperature cycles) and under realistic traffic loads. The discrepancy often lies between proof-of-concept studies and those aiming for generalizable, robust models. The lack of standardized protocols for the validation and calibration of these integrated models remains a significant concern, leading to difficulties in objectively comparing, assessing, and ultimately adopting different proposed approaches across the industry.

5. Gaps in the Current Literature

Despite the substantial progress achieved in integrating GPR and rheological modeling for pavement performance prediction, several critical gaps persist in the current body of literature. Addressing these gaps is crucial for advancing the field and realizing the full potential of this interdisciplinary approach.

5.1. Lack of Robust, Generalizable GPR-Rheological Constitutive Relationships

While research has yielded some empirical correlations between GPR-extracted properties and rheological parameters, a universally applicable and mechanistically sound relationship is still largely absent. Most existing correlations are site-specific, highly dependent on the particular asphalt mixture, environmental conditions, and GPR system used. There is a significant gap in developing fundamental, physics-based relationships that link GPR-derived properties (beyond simple thickness and dielectric constant) directly to complex rheological parameters such as non-linear viscoelastic parameters (e.g., damage evolution laws), viscoplastic parameters, or fatigue damage accumulation parameters. This limits the transferability and broad utility of current models.

5.2. Limited Integration with Multi-Scale Rheological Models

Current research predominantly focuses on integrating GPR data with macro-level rheological models, which describe the overall behavior of the asphalt concrete mixture. However, a significant gap exists in effectively linking macro-scale GPR observations (which inherently represent averaged material properties over a certain volume) to micro-scale rheological models. These micro-scale models delve into the behavior of the asphalt mastic, the aggregate-mastic interface, and aggregate interlocking, which are critical for understanding damage initiation and propagation at a more fundamental level [8]. Bridging this gap could provide a deeper, more predictive understanding of how material properties sensed by GPR translate into fundamental distress mechanisms.

5.3. Inadequate Consideration of Environmental Factors on GPR Signal Interpretation

The influence of fluctuating environmental factors—specifically temperature, moisture content, and aging—on asphalt's dielectric properties, and consequently on GPR signal interpretation, is often acknowledged but not fully accounted for in the development of robust GPR-rheological models [12, 15]. These factors can significantly alter GPR signal characteristics, leading to erroneous interpretations of underlying material properties if not properly corrected. There is a pressing need for more advanced, dynamic correction algorithms or the seamless integration of real-time environmental sensor data into GPR data processing and interpretation pipelines to ensure reliable material property extraction under diverse field conditions.

5.4. Limited Long-Term Field Validation Studies

Many existing studies demonstrate the theoretical potential or short-term applicability of integrated approaches through laboratory-based experiments or limited field trials. However, there is a significant and critical gap in comprehensive, long-term field validation studies. Such studies would involve collecting GPR data over extended periods on in-service pavements, systematically correlating these data with actual, measured pavement performance (e.g., quantified rutting, cracking, and roughness progression), and using these real-world observations to refine and rigorously validate the integrated rheological models. Without extensive long-term validation under diverse operational conditions, the predictive power and reliability of these integrated models remain largely unproven for practical application.

5.5. Uncertainty Quantification in Integrated Models

The inherent uncertainties associated with GPR measurements (e.g., signal noise, calibration errors), the derivation of material properties from GPR signals, and the parameters within rheological models are often not fully quantified or systematically propagated through the entire integrated prediction framework. This lack of rigorous uncertainty quantification limits the reliability and trustworthiness of the pavement

performance predictions and hinders effective risk assessment in pavement management decisions. A comprehensive understanding of these uncertainties is vital for providing confidence bounds on predictions and for making informed, risk-based engineering judgments.

5.6. Lack of Standardization for Data Acquisition and Processing

Currently, there is no widely accepted standard for GPR data acquisition parameters, signal processing techniques, and material property extraction for integration with rheological models. This absence creates significant challenges in comparing research findings, replicating results, and hindering broader adoption of these integrated technologies in practical pavement engineering.

5.7. Limited Exploration of Machine Learning for Direct GPR-to-Performance Mapping with Rheological Insights

While some studies have explored the use of machine learning for direct GPR-to-performance prediction [19], there remains a gap in developing "physics-informed" machine learning models. These models would not simply learn empirical correlations but would leverage established rheological principles and physical laws to guide the learning process. By embedding mechanistic constraints or features derived from rheological theory, such models could lead to machine learning models that are not only highly predictive but also more robust, interpretable, and generalizable for predicting pavement performance from GPR data, overcoming the "black-box" nature of purely data-driven models.

6. Suggestions for Future Research

Based on the identified gaps and ongoing debates within the current literature, the following areas are suggested as fertile ground for future research, aiming to advance the integrated rheological modeling of asphalt concrete using GPR-extracted properties for pavement performance prediction:

6.1. Development of Mechanistic-Empirical Relationships between GPR Signatures and Rheological Parameters

Future research should prioritize the development of fundamental, physically-based relationships that directly link specific GPR signal characteristics (e.g., frequency-dependent attenuation, dispersion, waveform morphology) to key rheological parameters of asphalt concrete (e.g., dynamic modulus master curve parameters, fatigue damage parameters, viscoplastic constants). This could involve sophisticated inverse analysis coupled with advanced material characterization techniques, utilizing multi-frequency GPR data and high-fidelity laboratory rheological testing. The goal is to move beyond empirical correlations to establish truly constitutive relationships driven by material physics.

6.2. Integration of Multi-Physics Models

A promising direction involves exploring the development of coupled multi-physics models that seamlessly integrate the principles of electromagnetic wave propagation (GPR physics) with the viscoelastic and viscoplastic constitutive laws governing asphalt concrete behavior. Such models would allow for a more direct and accurate simulation of GPR signals based on varying pavement material properties and, conversely, enable the direct inference of mechanical properties from GPR measurements through a unified framework. This approach could lead to a deeper understanding of the interaction between GPR signals and the complex mechanical response of asphalt.

6.3. Advanced GPR Data Inversion Techniques for Spatially Varying Rheological Properties

Further development and refinement of sophisticated GPR inversion algorithms are crucial. These algorithms should not only be capable of accurately determining layer thicknesses and average dielectric constants but also possess the ability to infer spatial variations in relevant rheological parameters within a given pavement layer. This would account for factors such as compaction variability, localized aging, or moisture ingress, providing a true 3D characterization of mechanical properties that is vital for localized performance prediction and targeted maintenance.

6.4. Development of Robust Environmental Correction Models for GPR Data

Comprehensive research is needed to develop sophisticated models that can accurately correct GPR signals for the dynamic effects of environmental factors, including temperature fluctuations, varying moisture content, and the aging process of asphalt. This could involve incorporating real-time environmental data from embedded sensors or using advanced meteorological models to adjust GPR interpretations, thereby enabling more reliable and consistent material property extraction under diverse and changing field conditions.

6.5. Long-Term, Large-Scale Field Validation Studies with Integrated Monitoring

A critical requirement for future research is the initiation and execution of extensive, multi-year field validation studies on in-service pavements. These studies must systematically collect GPR data alongside traditional destructive laboratory tests (via cores) and, crucially, long-term pavement performance measurements (e.g., rutting, cracking, roughness progression, IRI). Such comprehensive, integrated monitoring is essential for rigorously establishing the predictive power, reliability, and economic benefits of integrated GPR-rheological models under realistic traffic and environmental conditions.

6.6. Uncertainty Quantification and Sensitivity Analysis

Future research should implement rigorous uncertainty quantification (UQ) frameworks to characterize and propagate the inherent uncertainties associated with

GPR measurements, the process of material property derivation from GPR signals, and the parameters within the rheological models. This will allow for the development of more robust, risk-based pavement performance predictions, providing engineers and decision-makers with confidence intervals on predictions and enabling more informed risk management strategies in pavement asset management.

6.7. Development of Physics-Informed Machine Learning Models

Leveraging the burgeoning power of machine learning, future research should focus on developing "physics-informed" machine learning models. This involves embedding fundamental rheological principles and known physical laws (e.g., conservation of energy, stress-strain relationships) directly into the model architecture or as constraints during the training process. Such an approach could lead to machine learning models that are not only highly predictive but also more robust, interpretable, and generalizable for predicting pavement performance from GPR data, overcoming the "black-box" nature of purely data-driven models.

6.8. Standardization of GPR Data Acquisition and Processing Protocols

A concerted effort is required to develop industry-wide standards for GPR data acquisition parameters, signal processing techniques, and the subsequent extraction of material properties for pavement engineering applications. Such standardization would significantly facilitate data sharing, enable direct comparison and benchmarking of different models and algorithms, and ultimately accelerate the broader adoption and practical implementation of these advanced integrated technologies within the pavement engineering community.

6.9. Exploration of Hybrid Approaches

Future research should investigate hybrid approaches that combine the unique strengths of GPR with other complementary non-destructive testing (NDT) techniques. For example, combining GPR with Falling Weight Deflectometer (FWD) measurements could provide a more comprehensive and synergistic characterization of pavement layers. GPR excels at continuous spatial mapping of layer thicknesses and dielectric properties, while FWD provides structural response and stiffness information. Their combined use could lead to more accurate and reliable estimation of rheological parameters and improved pavement condition assessment.

7. Conclusion

The integration of GPR-extracted layer properties with advanced rheological modeling for pavement performance prediction represents a pivotal advancement in pavement engineering. The field has evolved significantly, moving from rudimentary GPR applications and empirical correlations to highly sophisticated mechanistic-empirical and machine learning-driven approaches. Despite this progress, substantial challenges and knowledge gaps persist, particularly concerning the development of universally

robust mechanistic-empirical relationships, the need for comprehensive long-term field validation studies, and the adequate accounting for dynamic environmental factors.

Addressing the identified gaps through targeted future research—prioritizing the development of generalizable, physics-informed models, establishing standardized methodologies, implementing rigorous uncertainty quantification, and conducting extensive long-term validation efforts—will be crucial. These concerted efforts are essential for fully realizing the transformative potential of this interdisciplinary approach, ultimately ushering in an era of more accurate, localized, efficient, and cost-effective pavement management practices.

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