



Review on Artificial Intelligence-Based Prediction of Asphalt Binder Aging and Pavement Distress

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ABSTRACT

Asphalt binder aging significantly affects the long-term performance and durability of flexible pavements, leading to various pavement distresses such as cracking, rutting, and raveling. Accurate prediction of asphalt binder aging and associated pavement deterioration is essential for effective pavement design, maintenance planning, and lifecycle cost management. In recent years, Artificial Intelligence (AI) techniques have emerged as powerful tools for modeling complex, nonlinear relationships among environmental factors, material properties, traffic loading, and aging characteristics of asphalt binders. This review paper explores the application of Artificial Intelligence–based methods for predicting asphalt binder aging and pavement distress. Various AI techniques such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Machine Learning (ML), Deep Learning (DL), and hybrid optimization models are examined in terms of their ability to analyze large datasets and provide accurate predictions. The study reviews existing literature on AI-driven predictive models that incorporate factors such as temperature variation, oxidation processes, traffic load, binder composition, and environmental conditions. Furthermore, the paper highlights the advantages of AI models over traditional empirical and mechanistic methods, including improved prediction accuracy, adaptive learning capability, and efficient data-driven decision-making. The review also identifies current research gaps, challenges in data availability, and opportunities for integrating AI with mechanistic–empirical pavement design approaches. Overall, the study provides a comprehensive overview of recent advancements in AI-based prediction of asphalt binder aging and pavement distress, emphasizing its potential to enhance pavement performance evaluation, optimize maintenance strategies, and support sustainable infrastructure development.

Keywords- Asphalt pavements, bleeding prediction, Artificial neural network (ANN), pavement performance, skid resistance, sensitivity analysis

I. INTRODUCTION

Flexible pavement conditions have an enormous impact on road safety and performance and are affected by a variety of factors like traffic patterns, climate, development parameters, construction methodology, and protective methods. Since service life depends on the flexible pavement situation, it is essential to conduct a control procedure as a management system of pavement. To ensure the long-term sustainability of roadways, minimize maintenance costs, and conserve resources, paving materials must be carefully chosen. The optimum design of both the pavement mixture and roadway is of great importance [1]. Artificial Intelligence (AI) is a branch of informatics in which computers perform human-like tasks, such as correctly detecting and learning inputs for perception, problemsolving, reasoning, knowledge representation, and planning. Different innovative AI technologies have been designed to mimic the cognitive capacities of humans to deal with more complex problems intentionally, intelligently, and adaptively. In general, AI may be considered a combination of machine learning



and data analysis [2]. Scientists hope to find more precious or attractive information underlying the physical effect of additives and experimental data. AI, as an evidence-based technique with high potential, has had success and dependability in many academic topics and projects. Therefore, this research systematically analyzed the utilization of AI in various types of flexible pavement, including pavement design, construction, cost, and maintenance. Prior studies on this topic over the last decade, especially since 2014, were gathered for this research. Specifically, the analysis aimed to distinguish the modern challenges and future headings of the research, allowing scientists to detect significant areas for subsequent study.

II. RESEARCH MOTIVATION

The process of bleeding involves the development of an asphalt binder film on the pavement's surface, which results in a bright, glass-like surface that typically becomes sticky. The pavement surface changes from being dark and black to becoming glossy, shiny, and glass-like. A bleeding pavement generates a smacking noise, similar to that observed when driving through rain. In hot climates, the aggregate gaps are filled with asphalt binder, which eventually spreads over the pavement surface. Asphalt binder develops on the surface of pavement over time, since bleeding is a phenomenon that cannot be reversed. Because bleeding decreases a vehicle's ability to resist skidding, especially on slippery roads, it can be deadly. It is typically seen in wheel pathways where aggregates are subsequently embedded as a result of the recurrent load cycle of tires (1). In previous studies on asphalt concrete, bleeding has been discussed as mostly is a permanent phenomenon (2). Bleeding is a maintenance issue that needs to be fixed promptly, either by corrective maintenance or, in uncommon circumstances, by emergency repair. The most popular treatments for bleeding include repairing the pavement with seal coat and bridging over the asphalt with aggregates of different types and gradations.

Wide-ranging studies have been conducted in recent years to create an independent method for analyzing skid resistance and recognizing different pavement flaws, such as cracks, ruts, raveling, and potholes. There is, however, no research that aims to automate the inspection of asphalt pavement bleeding in comparison with other pavement problems, such as cracking, rutting, or potholes. Owing to the capacity for learning and adapting, artificial neural networks (ANNs) have recently been employed in many areas of civil engineering to model the characteristics and behavior of materials, as well as to discover complicated relationships between various characteristics. Moreover, the use of ANNs to predict the permanent deformation of asphalt concrete mixtures modified by nano-additives has been investigated (3).

III. OVERVIEW OF NEURAL NETWORKS

Imitating the biological nervous system, neural networks are information processing computational tools capable of solving nonlinear relations in a specific problem [11-14]. Like humans, they have the flexibility to learn from examples by means of interconnected elements, namely neurons. Neural network architectures, arranged in layers, involve synaptic connections amid neurons which receive signals and transmit them to the other via activation functions. Each connection has its own weight and the network 'learns' by adjusting the weight between neurons to minimize error between the predicted and expected values. Also, in the learning process node biases are also adjusted in addition to the connection weights. Since interconnected neurons have the flexibility to adjust the weights, neural networks have powerful capacities in analyzing complex problems. Neural networks motivated



into regional climate behavior. To address spatial heterogeneity in thermal loading, a national climate zoning scheme was developed using k-means clustering, enabling targeted material performance assessment across climate zones. Within this framework, four predictive models were designed and evaluated: a climate-driven multiple linear regression model (C-MLR), an annual climatic pavement stress model (ACPS), a physically-informed heat flux model (H-FLUX), and a symbolic regression model based on linear genetic programming (LGP). Bayesian optimization and Limited-memory Broyden–Fletcher–Goldfarb–Shanno with Bounds (L-BFGS-B) tuning enhanced each model's predictive accuracy, with LGP outperforming others while maintaining model interpretability.

Yi Da et al.[2] The digitalisation of transport infrastructure helps extend pavement service life by enabling timely maintenance based on real-time data from automated inspection. This paper aims to review recent advancements in smart technologies and materials for the structural health monitoring (SHM) of asphalt pavements. Smart monitoring technologies are discussed by analysing their capability in the real-time automated inspection of early-stage pavement internal distress. Furthermore, smart pavement materials, particularly self-sensing asphalt materials, are reviewed in terms of their functionalities, fabrication and electrical characterisation. Finally, applications and challenges of self-sensing asphalt pavements are evaluated, including their implementation, engineering performance, and life cycle assessment.

Shadi Hanandeh et al.[3] This study used Artificial Neural Networks (ANN) to investigate correlations between the type and severity of distresses with a group of factors related to the trees and site conditions to identify the tree species that lead to pavement distresses and damage by using Pavement Condition Index (PCI). A Finite Element Model (FEM) was developed to represent two scenarios, with and without the trees, for both curb trees and median trees to highlight the effects attributed solely to the trees. The analysis results provide strategies and plan for tree farming along roads depend on the research results and scientific. In a finite element model that ignores tree-root effects, deformation achieves an upper limit of 0.57 mm below the outer vehicle wheel, while the internal load produces 0.43 mm of deformation, with strains in the x, y, and z directions far below failure limits. When tree-root movements are observed on a traffic-free road, deformations around the roots may reach over 25 mm, affecting a seven-fold wider area than the root zone. In Model 1, vertical displacements above the roots vary between 0.6 cm and 3 cm, indicating pavement expansion. Root pressure causes tension and compression zones to emerge, which can lead to injury. The stress and displacement characteristics in Model 2 are unbalanced due to the trees being planted in the median. Vertical displacements around the roots might reach four centimeters, suggesting serious damage.

Ran Zhang et al.[4] Asphalt pavement is the main type of pavement structure in China, and it accounts for more than 90% of the large-scale road network. As the service life of asphalt pavement increases, the demand for maintenance is increasing significantly. Accurately revealing the degradation mechanism and predicting the performance of asphalt pavement is the basis for the scientific maintenance decisions. Meanwhile, it is also beneficial for road construction planning and resource allocation. Based on numerous current studies, this review firstly provides a comprehensive summary of the internal factors such as structure and material, as well as external factors such as environment, load, and construction, that impact the performance of asphalt pavement.



Simultaneously, the degradation trend of asphalt pavement performance under intricate conditions is also clarified.

Atousa Nasertork et al.[5] Enhancing pavement distress inspection is crucial within a pavement management system. Recognizing the advantages of automated pavement condition inspection, considerable efforts have been invested in developing more efficient systems for this purpose. Raveling, a common asphalt pavement distress, significantly impacts both passenger comfort and pavement durability. Given its connection to pavement texture and the limited effectiveness of earlier inspection systems, improving automatic raveling inspection has become a challenging endeavor. This study proposes an image-based system for raveling detection, employing a new image processing-based feature set. This approach generates enhanced inputs for artificial intelligence models, thereby improving the efficiency of raveling inspection while optimizing resource allocation.

Lei Chen et al.[6] Based on the visualization analysis method of bibliometrics, 1268 core academic papers in the fields of self-sensing, self-energy harvesting, self-snow melting, self-cleaning, self-temperature regulation, and self-healing from January 2020 to June 2025 were summarized using literature on intelligent asphalt pavement technology collected from China National Knowledge Infrastructure and Web of Science databases as data sources. The changes in the number of publications on intelligent asphalt pavement technology at different times and in various countries and their underlying relationships were explored. The knowledge structure and research hotspots in this field were revealed. It provides hot clues and prospects for intelligent asphalt pavement technology research.

Sajad Ranjbar et al.[7] Pavement management systems play a vital role in maintaining transportation infrastructures by evaluating pavement distress to perform maintenance tasks efficiently. Severity analysis is an important step in this process. With an increasing focus on automating the pavement distress inspection, challenges persist, including limited attention to severity analysis of texture-based distresses and lack of applying fuzzy systems in this analysis despite the linguistic and qualitative description of severity levels. Accordingly, this paper presents a methodology leveraging computational intelligence frameworks such as fuzzy logic and metaheuristic optimization to develop a reliable system for severity analysis, particularly focusing on asphalt pavement bleeding.

Sina Mousavi et al.[8] Rad Several state agencies are in the process of implementing Balanced Mix Design (BMD), which involves using performance-related testing rather than relying solely on Superpave volumetrics to evaluate asphalt mix properties. BMD implementation efforts in Oklahoma are underway using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and the Hamburg Wheel Tracking Test (HWTT) to assess cracking and rutting resistance, respectively. As agencies transition from Superpave volumetrics to BMD, understanding the effects of mix parameters on the performance properties is crucial. This study evaluates cracking and rutting resistance of various plant-produced mixes in Oklahoma and develops predictive models for Cracking Tolerance Index (CT_{Index}). Thirty-four mixes, representing various materials and commonly mix designs, were sampled across Oklahoma and tested using IDEAL-CT and HWTT. IDEAL-CT was conducted on Long Term Oven-Aged (LTOA) mixes.



Masoud Toghrol Tabrizi et al.[9] Effective pavement maintenance is essential for ensuring road safety, minimizing lifecycle costs, and improving ride quality. One of the key challenges in pavement management is accurately evaluating the performance of rehabilitation treatments under varying environmental and structural conditions. This study proposes a comprehensive framework for evaluating the effectiveness of asphalt overlay treatments on flexible pavements, using the International Roughness Index (IRI) as the primary performance metric. Drawing on data from the Long-Term Pavement Performance (LTPP) program's Specific Pavement Study 5 (SPS-5) sites, this study evaluates both the short-term and long-term effectiveness of pavement rehabilitation treatments. A Multiple Linear Regression (MLR) model was developed to predict immediate improvements in IRI, achieving an adjusted R^2 of 0.8237 based on five key explanatory variables. For long-term performance, an Artificial Neural Network (ANN) model captured complex deterioration patterns with a high prediction accuracy ($R = 0.987$).

Rabea Al-Jarazi et al.[10] Interface bonding between asphalt layers plays a vital role in ensuring the proper functionality of pavement structures. Interlayer Shear Strength (ISS) is recognized as an indicator quantifying the interface bonding quality. Consequently, accurate evaluation and prediction of the ISS is imperative in determining the performance of asphalt pavement structures. By conducting laboratory experiments and employing machine learning (ML) techniques, this research aims to predict and assess the ISS in asphalt pavement. In this regard, the classification and regression trees (CART) model was proposed based on measured data collected from laboratory experiments. Three experimental factors of curing temperature, normal stress, and tack coat application rate were selected as variables. The findings showed that the developed CART model explained over 98% of the experimental data in a relatively short period.

Zhe Zeng et al.[11] Reflective cracking, the phenomenon by which cracks propagate through the overlay from existing damaged pavement, is a major cracking distress for asphalt pavements. Over time, researchers have developed various models to simulate the progression of reflective cracking. These models can be categorized into four approaches: crack-based, crack with fracture process zone at the tip, damage with smeared cracks, and microdamage-based. This paper provides a state-of-the-art review of the available models, including asphalt mixture cracking resistance models and their related structural analyses. For each model, the guiding principles, experimental protocols, model requirements, and outputs are reviewed and summarized. After comparing the strengths and weaknesses of each categorized model, the progress made over the years in modeling asphalt mixture fracture is discussed in terms of model diversity, extent of structural analysis, computational techniques, and material testing. However, challenges persist in two key aspects: (1) combining multiple mechanisms and/or failure modes, and (2) striking a balance between model advancements while ensuring practicality.

Mahmoud Khadijeh et al.[12] Asphalt binders are critical for asphalt pavement performance, and understanding their rheological behavior is essential for designing durable roadways. The complex shear modulus and phase angle (δ) are primary parameters characterizing binder rheology. This study introduces a novel hybrid machine learning model combining deep neural networks (DNN) and Gaussian process regression (GPR) to predict and δ for bituminous binders and binder-filler systems (mastics). DNN excel at capturing complex, nonlinear



relationships among eleven binder and thirteen mastic input parameters, including aging conditions, chemical and physical properties, and test parameters.

Lara Sucupira Furtado et al.[13] This article explores the connection between Smart City advancements and the development of materials and strategies for asphalt pavements. It highlights the synergy between Smart Cities and Industry 4.0 through current technological advancements using connectivity, artificial intelligence, and big data analysis. The relationships between Smart Cities and Industry 4.0 are examined with an emphasis on five major areas: (i) Internet of Things and integrated systems; (ii) robotics and additive manufacturing; (iii) augmented reality for modeling and simulations; (iv) data-driven analysis: big data, artificial intelligence; and (v) citizen participation.

Xue Luo et al.[14] Viscoelastic materials are widely used in fields such as transportation engineering, biomedical systems, and polymer science. Their strong nonlinearity, time-dependent behavior, and coupled multiphysics responses pose substantial challenges for modeling and analysis. Conventional constitutive models typically rely on a large number of experimental parameters and physical assumptions, which limit their ability to accurately capture the complex, multi-scale, and multiphysics behaviors of viscoelastic materials. In recent years, Physics-Informed Neural Networks (PINNs)—a mesh-free framework that integrates physical governing equations with deep learning—have demonstrated distinct advantages in modeling material behaviors. PINNs not only accurately solve partial differential equations (PDEs) via automatic differentiation but also maintain strong predictive capability under sparse data and incomplete boundary conditions.

Xueting Wang et al.[15] With the acceleration of urbanization comes the urban ‘heat intensification’ phenomenon due to artificial heat sources, building structures, and road heat storage, commonly known as the urban heat island effect (UHIE), thereby increasing the demand for building cooling daily. Phase change materials (PCMs) have become the optimal energy storage solutions for energy conservation and environmental protection, playing a crucial role in temperature regulation. In transportation pavement engineering, PCMs demonstrate stable energy storage effects that achieve a balance between energy supply and demand, representing a revolutionary development in road energy conservation. This paper first summarizes the preparation techniques of PCMs applied in cooling pavements and describes the heat conduction theory of asphalt pavements and the phase change heat transfer process. Subsequently, the cooling efficiency of PCMs in cooling pavements and building structures was compared to analyze the contribution of PCMs to mitigating the UHIE. The results indicate that PCMs can effectively moderate the temperature fluctuations in the surrounding environment while reducing energy load. However, to achieve higher temperature control efficiency, setting the heat outlet of the temperature control system is essential, which involves the heat induction orientation of the system and is closely related to the material's thermal conductivity. Lastly, in the context of the big data era and the rapid development of computer science, this article anticipates the potential application of AI and machine learning (ML) in realizing the deployment of energy storage materials in green transportation construction.

VI. CONCLUSION

The review highlights the significant potential of Artificial Intelligence (AI) techniques in predicting asphalt binder aging and pavement distress. Traditional empirical and mechanistic methods often struggle to accurately



model the complex interactions among material properties, environmental conditions, traffic loading, and aging processes. In contrast, AI-based approaches such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Random Forest, and deep learning models are capable of analyzing large datasets and capturing nonlinear relationships, resulting in improved prediction accuracy and reliability. The literature indicates that AI-driven models can effectively predict important pavement performance indicators such as rutting, cracking, fatigue life, and pavement condition index. These models help transportation engineers better understand pavement deterioration patterns and support proactive maintenance and rehabilitation planning. Additionally, recent studies integrating AI with sensor data, remote sensing, and IoT technologies demonstrate the potential for real-time monitoring and large-scale assessment of pavement aging. Despite these advancements, several challenges remain, including limited high-quality datasets, model interpretability issues, and the need for standardized data collection methods. Future research should focus on integrating hybrid AI models, improving data availability, and combining AI techniques with mechanistic–empirical pavement design frameworks to enhance prediction capability. Overall, Artificial Intelligence offers a promising and efficient approach for predicting asphalt binder aging and pavement distress, contributing to more sustainable pavement management, optimized maintenance strategies, and improved long-term performance of road infrastructure.

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