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Advances in Micromechanical Modelling of Asphalt Mixtures in Flexible Pavements and their Potential use in the Design Process: A Review

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ABSTRACT

This review explores the transformative impact of micromechanical modeling on flexible pavement design, addressing challenges posed by traditional uniform loading assumptions, particularly in the context of heavy truck tires. From the pioneering work of Chang and Meegoda in 1997 to recent studies by Al Khateeb et al. in 2021, micromechanical modeling explores the microstructural behavior of asphalt mixtures. Seminal contributions emphasize aspects such as shear fatigue performance, tire-pavement contact pressure, and inter-particle effects on asphalt microstructure. Notable works underscore the crucial role of tire-pavement interactions. Recent applications, such as studies on porous asphalt mixtures and coupling effects in asphalt microstructure, exemplify the diverse range of insights derived from micromechanical modeling. Beyond material characterization, the review explores the integration of these models into the pavement design process, promising resilient, sustainable, and cost-effective solutions that align with real-world pavement responses to heavy traffic loads. In conclusion, micromechanical modeling emerges as a powerful tool, empowering pavement engineers to design sophisticated systems for optimized performance and longevity in the evolving landscape of transportation demands.

Keywords: Micromechanical modeling; flexible pavement design; asphalt mixtures; uniform loading; heavy truck tires; shear fatigue; tire-pavement interactions; inter-particle effects; sustainable pavement; resilient design.

1 INTRODUCTION

Flexible pavements, integral to our transportation infrastructure, grapple with enduring challenges amid the demands of modern society. Their performance and longevity hinge on often underestimated factors, such as the profound impact of heavy truck tires on road surfaces. Traditional pavement design methods, laden with simplifications like uniform loading assumptions, overlook the intricate complexities tied to tire-pavement interactions, resulting in premature pavement distress and escalating maintenance costs ([1]; [2]; [3]).

In response, the field of pavement engineering is undergoing a transformation with the integration of advanced micromechanical modeling techniques [4]; [5]. Micromechanical modeling delves into the microstructural behavior of asphalt mixtures within flexible pavements [6]; [7], offering insights that bridge the gap between micro and macro scales of pavement behavior (Ticking et al., 1987; Zhang et al., 2001; Dubois et al., 2012). Seminal studies by [4] pioneered micromechanical simulations of hot mix asphalt (HMA), igniting this innovative approach. Researchers like [5] furthered the field by investigating shear fatigue performance, elucidating the influence of various factors. Pivotal work by [1] underscored the importance of tire-pavement contact pressure and its

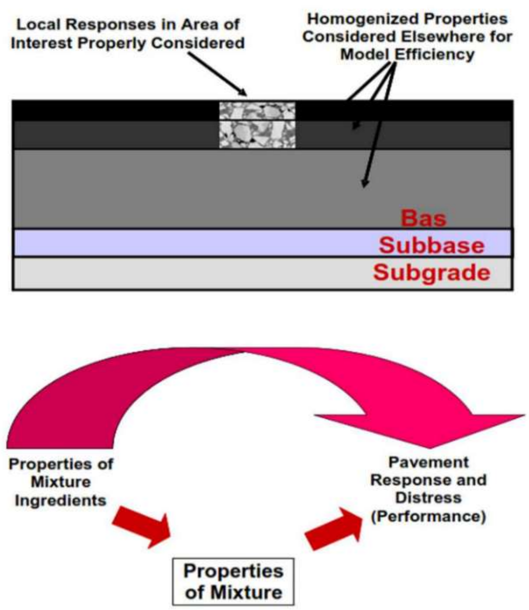

Figure 1 - Visual Representation of the Multi-stage process involving the Micromechanical Modelling of Asphalt Mixtures and Traditional Approach to Design [23]

effects on pavement strain. This research, followed by [2] and [3], paved the way for a better understanding of tire-pavement interactions and precise contact pressure modeling [2]; [3].

Micromechanical modeling has significantly contributed to assessing asphalt mixture behavior under diverse conditions [6]; [7]). [6] used the finite element method to simulate the elastic response of asphalt materials, while [7] predicted fracture damage in asphalt mixtures via the cohesive zone fracture method. Recent studies, exemplified by [8], simulate the micromechanical behavior of porous asphalt mixtures during compaction, providing insights into temperature effects on compactability [8]. Additionally, [9] investigate coupling effects between inter-particle behavior and imperfect interfaces in asphalt mixtures, shedding light on asphalt microstructure complexities [9]. These studies represent a fraction of the extensive body of research illuminating micromechanical modeling's potential in enhancing our understanding of asphalt mixture behavior in flexible pavements [2]; [3]. This review paper synthesizes these findings, explores their implications for pavement design, and offers a comprehensive overview of the current state of the art. Micromechanical modeling holds transformative potential to redefine pavement design by capturing nuances of tire-pavement interactions and microscale stress concentrations [1]; [2]; [3]). This approach allows for a comprehensive understanding of pavement behavior, ultimately leading to safer, more enduring, and environmentally sustainable transportation infrastructure.

2 MICROMECHANICAL MODELLING OF ASPHALT MIXTURES

In the domain of pavement engineering, the traditional assumption of uniform loading in pavement design has long posed challenges, especially concerning the impact of truck tires on road surfaces. To address this limitation, recent years have witnessed a significant paradigm shift, with advanced micromechanical modeling techniques being integrated into the pavement design process. Chang

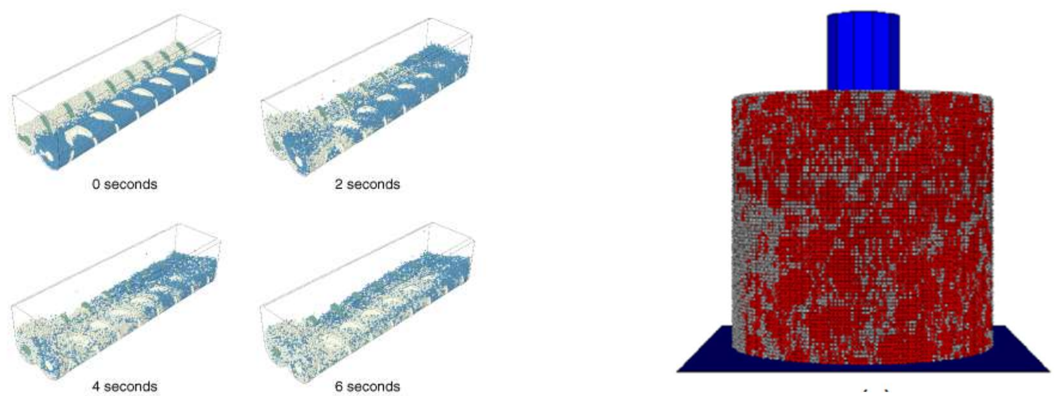

Figure 2 - How a Discrete Element Model works ([20]) and DEM used by [7]

and Meegoda (1997) initiated this transformation by introducing a discrete element model for Hot Mix Asphalt (HMA), setting the stage for subsequent research on micromechanical modeling [4]. Building on this foundation, Peng et al. (2020) delved into the shear fatigue performance of asphalt mixtures, providing insights into the micromechanical aspects of behavior [5]. In comparison, [6]; [7] & [10] worked on the finite element method (FEM) to investigate various aspects of asphalt mixtures. In particular, [6]simulated the material behavior of asphalt by incorporating a network of special frame elements with a stiffness matrix to predict the load transfer between cemented particles. Their research provided insights into the elastic response of asphalt materials [6]. After which [7]predicted crack-associated fracture damage in asphalt mixtures using FEM in conjunction with a cohesive zone fracture method. Their approach allowed for a more advanced characterization of microstructural damage evolution, mixture heterogeneity, inelastic material behavior, and interactions among mixture [11] constituents [7].

Further, [9] presented a model considering inter-particle effects and imperfect interfaces within asphalt mixtures [9]. [8] simulated the micromechanical behavior of porous asphalt mixtures during compaction [8]. In the realm of sustainable pavement, investigated the modulus of recycled asphalt, while [12] considered the effects of the interfacial zone in Hot Mix Asphalt (HMA) [11]; [12]. [13] proposed an approach to simplify the geometry of mixture microstructures for more efficient simulation.

3 INFLUENCE OF TYRE FOOTPRINT CONTACT AREA AND PRESSURE DISTRIBUTION ON THE ROAD

The contact between vehicle tires and road surfaces is a critical interaction that profoundly

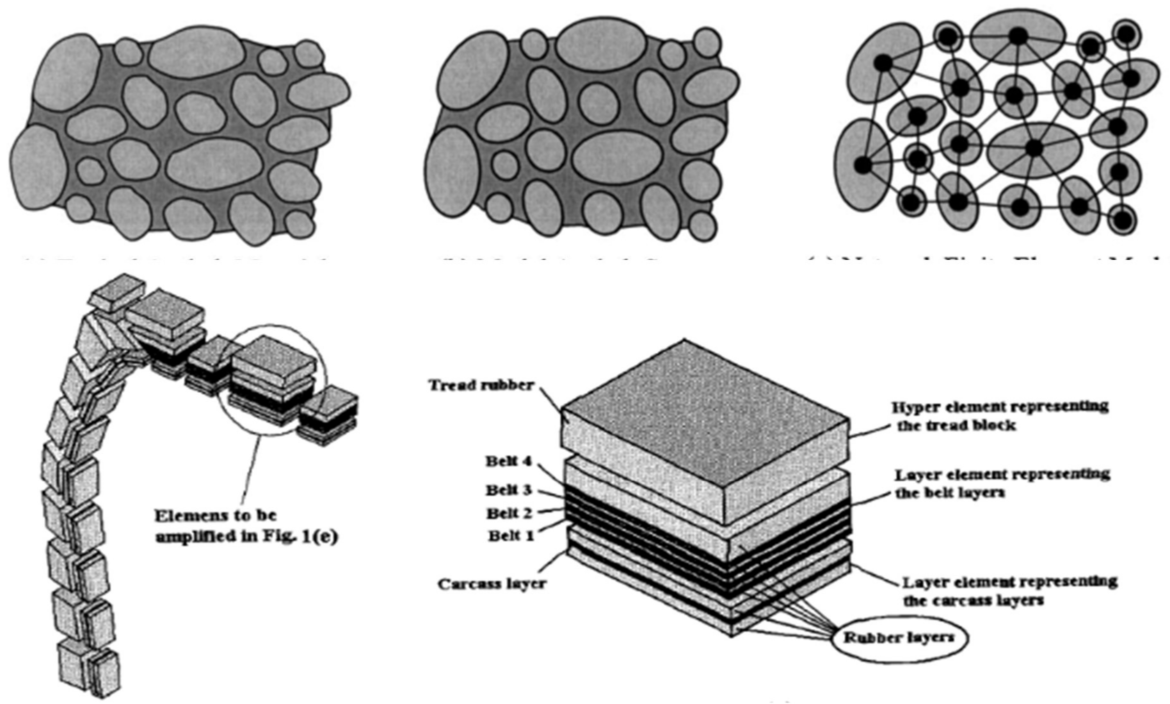

Figure 4 - Meshing of tire and FEM of the rubber blocks used by [2]

influences the performance and longevity of pavements. Understanding the intricate details of this interaction, particularly the contact area and pressure distribution, has become paramount in pavement engineering. Several research endeavors have shed light on this aspect, providing valuable insights into the influence of tire footprint contact area and pressure distribution on the road surface. [1] embarked on pioneering work by introducing the concept of tire contact pressure and its effect on pavement strain. Their study, which introduced a finite element tire model, laid the foundation for understanding the importance of tire-pavement interaction. Subsequent investigations delved deeper into the complexities of tire-road interactions. [2] proposed a novel methodology for estimating tire-road contact pressure distribution through 3D pressure field analysis. This approach provided a more comprehensive understanding of the complex interactions between tires and road surfaces, especially regarding pressure distribution [2]. [3] took a numerical approach to evaluate tire/road contact pressures, utilizing innovative iterative methods and classical image processing. Their work aimed to understand the real-world implications of contact pressure on roads, offering insights into the damage received by the road under various contact pressures. [15] quantified local pressure distribution and actual contact areas between tires and road surfaces. By doing so, they provided valuable information on the dynamics of tire-road interaction, shedding light on the distribution of local pressures and contact areas. [16] focused on utilizing a tire footprint system to capture contact pressure patterns both statically and dynamically. Their study added to the body of knowledge regarding the intricate interactions between heavy vehicle tire contact pressure and pavement responses, contributing to a better understanding of pavement sustainability. [17] proposed a semi-analytical model that considered road surfaces as flat and tires as smooth, focusing on specific parameters like tire pressure, axle loading, and tire shape. The model aimed to offer a more realistic representation of tire-pavement contact while being computationally more efficient than traditional finite element methods. In addition, [18]; [19] investigated the tire-pavement contact behavior in full-scale tests for heavy trucks; their study focused on characterizing tire-pavement contact stress distribution using a 3D scanner and the sand patch method. Their results reveal the influence of pavement texture on contact behavior and provide insights into the distribution of contact stress under different conditions for their target study. [20] focused on analysis the tire contact interaction taking in account a simplified pavement with different aggregate sizes using a FEM approach; their results showed that the pavement texture significantly affected the contact behavior and that the proposed model can assess tire-pavement contact behavior, providing insights into pavement skid resistance. Additionally, [14] evaluated the resistance to thermal cracking in bituminous composites containing granular particulates, advancing the understanding of thermal stress in asphalt mixtures. [15] in turn focused on developed an Artificial Neural Network model for Predicting the Contact Area of Tractor Tyers on a firm surface whereas [16] using an innovative 3D scanning method to evaluate the tire footprint in soil; their results showed the requirement for an increased emphasis on considering footprint depth as a significant parameter influencing tire-soil contact area.

4 INCORPORATING MICROMECHANICAL MODELING IN PAVEMENT DESIGN

The integration of micromechanical modeling into pavement design represents a significant shift in the paradigm of designing and analyzing flexible pavements. Traditional pavement design has long relied on simplified assumptions of uniform loading and material behavior. However, the reality of pavement responses to heavy traffic loads, especially those from truck tires, often deviates substantially from these assumptions, leading to premature pavement distress and reduced service life. The incorporation of micromechanical modeling techniques has emerged as a powerful solution to address these challenges and pave the way for more robust, sustainable, and efficient pavement designs. [4] marked one of the initial forays into micromechanical modeling by simulating Hot Mix Asphalt (HMA) using a discrete element model. Their work, aligned with the Strategic Highway Research Program's (SHRP) experimental results, played a pivotal role in shaping subsequent research on discrete element model methodology in the context of asphalt mixtures. Subsequent studies have further expanded the scope of micromechanical modeling, encompassing various aspects of asphalt mixture behavior, including shear fatigue performance [5], fracture damage prediction [7], and inter-particle effects and imperfect interfaces [9]. The critical tire-pavement interaction, which has been historically oversimplified in traditional pavement design, has also received considerable attention through micromechanical modeling. Researchers have explored tire contact pressure [1], contact pressure distribution [2], and the implications of contact pressure on road surfaces [3]. This body of work has provided invaluable insights into the complexities of tire-road interactions. The advantages of micromechanical modeling are not limited to material characterization and tire-pavement interactions; they extend to understanding local pressure distribution and actual contact areas between tires and road surfaces [15]; [16]. Furthermore, semi-analytical models have been proposed to achieve a more realistic representation of tire-pavement contact, considering parameters like tire pressure, axle loading, and tire shape [17]. The inclusion of micromechanical modeling in pavement design holds the promise of revolutionizing the industry. By capturing the intricate details of material behavior, tire-road interactions, and local pressure distribution, these models provide a more accurate representation of real-world pavement responses. This newfound understanding allows for the design of pavements that are not only more resilient to the stresses induced by heavy traffic loads but also more sustainable and cost-effective in the long term. As the field of micromechanical modeling continues to evolve, it is poised to become an integral tool in the pavement engineer's toolbox, ushering in a new era of pavement design and management.

5 CONCLUSIONS

The advancements presented in this review underscore the necessity of departing from traditional assumptions of uniform loading and material behavior. The integration of micromechanical modeling techniques has proven to be a transformative approach, offering a deeper understanding of the microstructural phases governing asphalt mixture behavior, the complexities of tire-road interactions, and the impact of contact area and pressure distribution on pavement responses. The reviewed research endeavors have collectively contributed to a burgeoning body of knowledge that empowers pavement engineers with the tools needed to design resilient, sustainable, and cost-effective roadways. Micromechanical modeling provides the means to capture the intricacies of real-world pavement responses, enabling the development of pavements that can withstand the rigors of heavy traffic loads and environmental factors. As the field of micromechanical modeling continues to evolve, its potential in pavement design and management becomes increasingly evident. By embracing these advancements and integrating them into the pavement engineering process, practitioners can look forward to a future where pavements are not just structures, but sophisticated systems designed for optimal performance and longevity.

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