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Investigation of Particle-Scale Responses of Asphalt Mixtures Under Non-Uniform Rolling Tire Loads

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Abstract.

As the degradation of asphalt pavement surfaces under traffic loads is the primary factor affecting road network costs, it is crucial to assess the mixture responses at a micro-structural level to better understand and model the mixture deterioration behavior under real tire load conditions. Currently, many investigations are conducted within the framework of continuum mechanics to study the asphalt mixture responses under tire loads, which fails to capture the heterogeneous and discontinuous nature of asphalt mixtures adequately. To address this limitation, this study introduces a novel approach, employing a Finite Element Method-Discrete Element Method (FEM-DEM) coupling strategy, for modeling the tire-pavement interaction under rolling conditions. This approach incorporates non-uniform tire loads derived from a FEM tire model into a DEM model of asphalt mixtures containing irregular particles. By utilizing this coupling algorithm, it becomes possible to analyze the responses of asphalt mixtures at the particle scale under realistic tire load conditions, thereby offering fresh insights for the design of pavement surfaces.

Keywords: Tire-pavement interaction, Finite Element Method, Discrete Element Method, FEM-DEM coupling, Asphalt mixture, Rolling tire loads.

1 Introduction

The road infrastructure is currently undergoing substantial transformations and encountering various challenges due to the escalating traffic volume and the effects of climate change. As the costs associated with road network maintenance primarily stem from the degradation of asphalt wearing layers, it becomes crucial to acquire a comprehensive understanding of asphalt mixture responses under real traffic loads at a microscopic level in order to optimize the design of asphalt pavement surfaces.

Discrete Element Methods (DEM) have emerged as a powerful tool for modeling the mechanical behavior of granular materials and have been extended to explore micro-mechanical behavior of asphalt mixtures due to their heterogeneous structure.

DEM treats materials as an assembly of discrete particles connected by contact interactions, enabling the study of particle-level behavior and deformation characteristics. This approach offers several advantages when investigating asphalt mixture responses under external loads. One significant contribution of DEM lies in its ability to provide micro-mechanical insights into the behavior of asphalt mixtures. Ouellet-Plamondon et al. [1] and Kamal Pour et al. [2] have demonstrated that DEM simulations reveal intricate particle rearrangements, interlocking phenomena, and contact force distributions within the mixture. These insights contribute to a deeper comprehension of the mechanisms governing load distribution and stress propagation, which are critical factors influencing pavement performance. The incorporation of realistic aggregate particles within the DEM framework is another notable advancement in modeling asphalt mixtures. Aggregate morphologies play a vital role in determining the overall mechanical properties of asphalt pavements. By explicitly representing aggregate shapes, researchers can assess the influence of aggregate characteristics, gradations, and distribution patterns on the mixture's mechanical response [3, 4]. Nevertheless, existing DEM models have primarily focused on simulating laboratory tests using asphalt mixture samples due to computational cost constraints. Additionally, the boundary loading conditions employed in most simulations tend to be uniform and oversimplified, thereby lacking accuracy in replicating realistic tire loading conditions.

Applying realistic tire loading boundary conditions on asphalt layers is a prerequisite to examining accurately pavement responses. Early experimental studies utilized pressure sensors and footprint measurements to analyze tire contact stresses [5, 6]. However, conducting experimental measurements using rigid sensors remains both costly and time-intensive. Additionally, extending these measurements to encompass specific loading scenarios like braking, acceleration, and cornering poses challenges. In contrast, numerical methods offer an efficient avenue for obtaining tire-pavement contact stress data. Finite Element Method (FEM) has been employed to simulate tire-pavement contact under various loading conditions, providing detailed stress distribution patterns and enabling the quantification of stress concentrations [7, 8]. The ability of FEM is also shown to simulate complex loading scenarios, including cornering and braking, and to capture transient stress variations [9, 10].

Several studies have been conducted within the framework of FEM to investigate the responses of asphalt pavements under traffic loads, employing processed tire loading data from measurements [11] or indirectly from tire models [12,13]. However, despite its capacity of simulating tire contact stresses on pavement surfaces with high precision, FEM still struggles in quantifying internal particle-scale responses of asphalt mixtures. On the other hand, some DEM models in 2D have been developed to explore asphalt layer responses under uniform tire loads, considering aspects such as surface wear [14] and crack development [15]. Nonetheless, using 2D models for predicting asphalt mixture performance may be unreliable due to their inability to fully describe the heterogeneous structure of asphalt mixtures. While DEM shows promise in examining the mechanical properties of asphalt mixtures at the particle level, it falls short in accurately simulating deformable tire structures and capturing realistic tire contact forces on pavement surfaces. Consequently, there is a need for a multi-scale

simulation that combines FEM and DEM to thoroughly investigate non-uniform tire loads on asphalt mixtures at the particle level.

In this study, we introduce a novel FEM-DEM coupling approach to investigate asphalt mixture responses at a particle scale under non-uniform rolling tire loads. The method integrates DEM to capture the internal discontinuity behaviors of asphalt mixtures at the particle scale. Meanwhile, FEM is employed to capture tire-pavement contact stresses that are subsequently applied to the asphalt mixture model as non-uniform loading boundary conditions. This method presents a pioneering and promising avenue for comprehending the underlying mechanisms of pavement degradation at a particle level induced by actual rolling tire loads.

2 FEM-DEM coupling for tire-pavement interaction

As research focused on simulating non-uniform tire loads on asphalt pavement using DEM models is notably limited, we introduce herein a pioneering approach involving the coupling of FEM and DEM. This strategy enables the simulation of non-uniform boundary conditions within particle assemblies. Due to the considerable stiffness of the pavement in comparison to the tire, the deformation of the pavement surface remains negligible when a tire moves across it for a brief duration. Therefore, an assumption can be made that the tire contact stresses during its rolling process remain unaffected by the pavement structure. In this context, when a tire is in steady motion, we can directly apply the force field derived from the FEM tire model to the surface of the DEM asphalt layer. Through this coupling technique, the need for internal calculations of tire elements and extensive contact detection between tire elements and asphalt mixture particles is obviated. As a result, computational efficiency is heightened without sacrificing precision. Moreover, the reduction in computational expense enables DEM tools to seamlessly integrate authentic particle shapes into simulations involving asphalt mixtures.

2.1 Asphalt mixture modeling

The composition of asphalt mixture is heterogenous and primarily consists of aggregates and asphalt mastic. For this investigation, we employed an asphalt mixture model previously developed [16], which incorporates particle morphology and size distribution into numerical simulations of asphalt mixtures. As depicted in Figure 2, the numerical sample of the asphalt layer was reconstructed using an open-source code LMGC90 [17]. Table 1 gives the aggregate gradation of BBSG (0/10) (semi-coarse asphalt concrete) that is widely used in asphalt wearing courses in France.

Table 1. Particle size distribution (PSD) of asphalt mixture

Diameter (mm)	12.5	10	8	6.3	4	2	1	0.5	0.25	0.125	0.063
PSD (%)	100	90	75	58	44	31	20	15	12	9	6.5

The simulation accounts for particle interactions through viscoelastic asphalt mastic, adopting the Burgers contact model, fine particles (diameter < 2 mm) are considered as components of asphalt mastic to balance the computation cost and numerical accuracy.

This model combines a Maxwell model in series with a Kelvin-Voigt model, where stiffness and viscosities for the Maxwell and Kelvin-Voigt components are represented by K_m , C_m , K_k , and C_k , respectively. Further elaboration on the numerical implementation of this contact model can be found elsewhere [18].

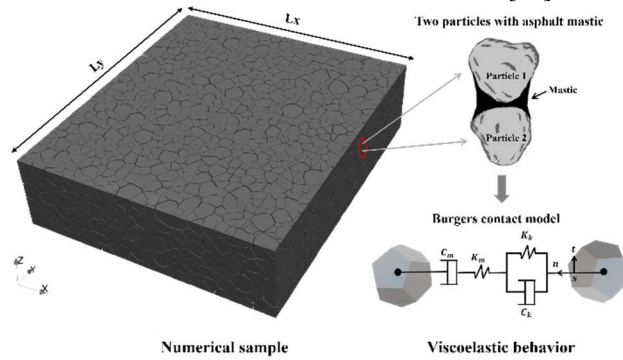


Fig. 2. Numerical DEM model of asphalt layer.

2.2 FEM-DEM coupling frame

The core of the FEM-DEM coupling mechanism revolves around the identification of corresponding particles within the asphalt layer that are in contact with the nodes encompassing the tire-pavement contact area, as shown in Figure 3. The contact forces exerted on all nodes situated within the tire footprint exhibit variations based on their specific positions.

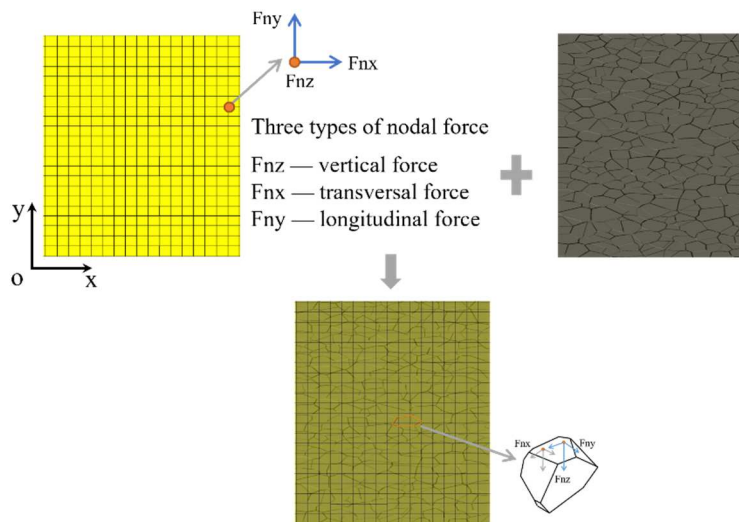


Fig. 3. Coupling simulation of FEM and DEM.

To achieve this objective, the process of detecting contacts between particles and mesh nodes is executed through a dual-tier approach. Initially, a preliminary coarse

detection phase employs the bounding box algorithm. This step involves pinpointing particles within the vicinity of a designated reference mesh region. Subsequently, when a mesh node is situated within this bounding box, fine detection is conducted using the cross-product method. This refined step serves to precisely determine which particle surface comes into direct contact with the tire's contact force nodal point.

Following the successful identification of the particles on the surface of the asphalt mixture layer that experience the tire contact nodal forces, the coupling simulation is set into motion utilizing iterative time-based calculations.

3 Validation of the numerical model

To verify the effectiveness of the proposed modeling approach, numerical simulations were further conducted. Using the coupling method, the tire loads were applied to the asphalt layer model as force boundary conditions. We studied the pavement responses after a short loading time (1×10^{-2} s) in order to simulate instantaneous dynamic loading. The time step was set to 5×10^{-5} s during the entire simulation to ensure numerical stability.

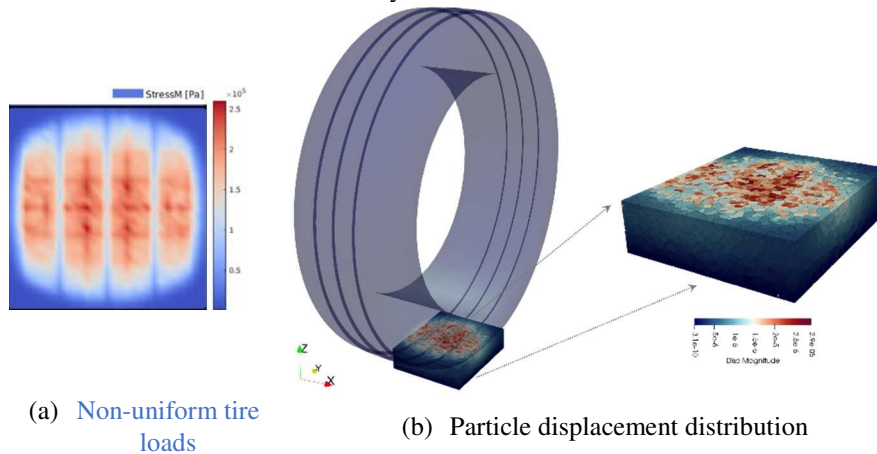


Fig. 4. Particle displacement distribution under non-uniform tire loads.

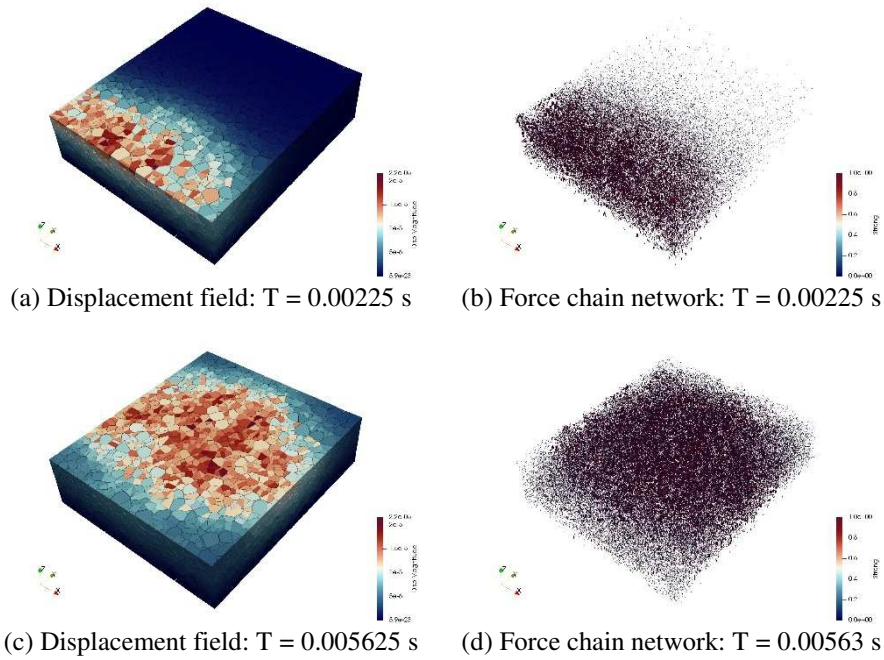
A representation of the magnitude of tire contact stresses on the pavement surface at a tire load of 5 kN is shown in Figure 4(a), using a tire of type 185/65R15 with an inflation pressure of 2.2 bar. Figure 4(b) shows the particle displacement distribution under real tire loads, in which the non-uniform tire loads are derived from a previous numerical tire model based on FEM [19]. Particle displacements are observed to be non-uniform on the asphalt layer surface. Particles near the center having greater displacements than particles in other regions, which is consistent with the tire-pavement contact stress concentration. In addition, there are differences in the contour color between particle displacements and applied contact stresses. The difference is caused by the non-uniformity of particle size distribution and particle contact-bearing capacity, big particles usually have more contacts from their surrounding particles and therefore

provide them more resistance to external forces and finally induce less fluctuation of particle motion.

4 Simulation under rolling tire loads

Following the validation of the coupling method, we investigate further the asphalt layer responses under rolling tire loads. In contrast with the static simulation, rolling simulation requires the external force field to advance on the asphalt layer surface over time. Thus, a rolling load simulation algorithm based on time-step calculation is used to conduct this rolling process. The coordinates of the external force field move step by step according to the applied tire rolling velocity over time through time advancement.

Figures 5(a), 5(c), 5(e), 5(g) give evolution results for the overall particle displacement distribution at tire velocity of 30 m/s along the time. As can be seen from the figures, the non-uniform external tire load advances along the y-direction on the asphalt layer surface, the particles move consistently with the tire load, which proves the reliability of the proposed coupling algorithm. As a result of the tire loading pass, a residual displacement field appears on the asphalt layer surface, which indicates a process of viscous material flow inside the asphalt mixture.



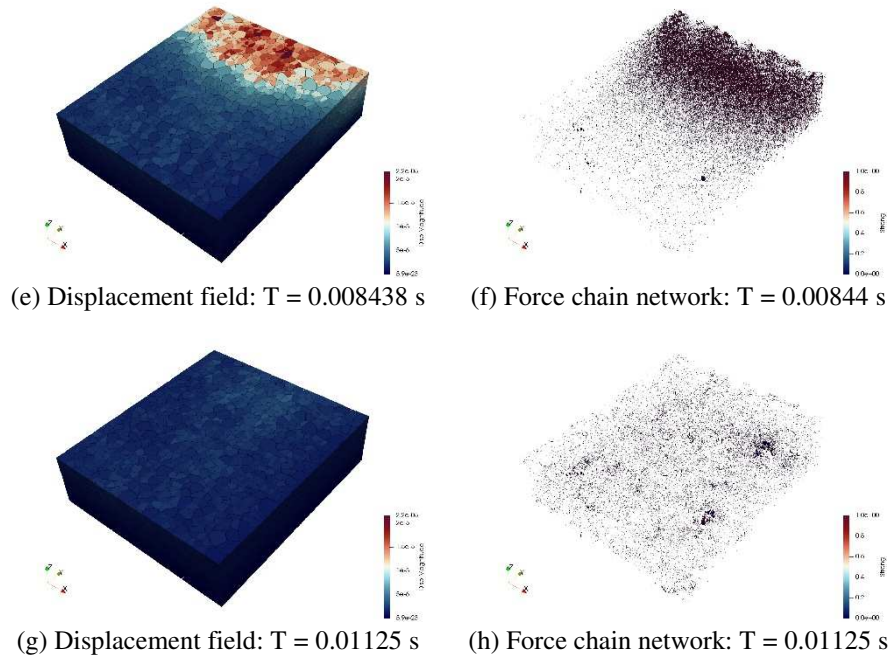


Fig. 5. Particle displacement distribution and contact force network (strong force = 1.0 and weak force = 0.0) evolution at tire rolling velocity of 30 m/s.

Figures 5(b), 5(d), 5(f), 5(h) show the strong and weak force distribution during the rolling process at a tire velocity of 30 m/s. In response to moving tire load, strong (red) and weak (blue) forces evolved. At the initial stage of rolling, the contact force network is considerably loose because only a little range of tire load activates on the layer surface. When the tire load is fully distributed on the mixture layer ($T = 0.00563$ s), the strong contact force network reaches its maximum distribution range. After that, as the tire load passes from the layer surface, the strength of force networks starts to diminish. A relatively equal balance of force states is finally achieved (after $T = 0.01125$ s) when the tire load fully passes the layer surface. The above analysis of the evolution of the contact networks shows how the tire is moving on the asphalt layer surface, also demonstrating the accuracy of the coupling algorithm.

5 Conclusion

In this study, a FEM-DEM coupling framework is established to delve into the intricate responses of asphalt mixtures to true-to-life tire loads at the particle scale. The primary conclusions drawn from this study are elucidated as follows:

To scrutinize the internal particle-scale reactions of asphalt mixtures when subjected to authentic tire loads, we conduct numerical simulations using the devised FEM-DEM coupling algorithm. The effectiveness of this coupling algorithm is firstly

substantiated through meticulous analysis of particle displacement distributions under static tire loads. Further, the evolution of particle displacement and contact force network under rolling tire loads across the asphalt layer surface demonstrates a coherent alignment with the loading process. These consistencies serve as a testament to the robustness of our coupling simulations.

The proposed FEM-DEM coupling strategy seamlessly amalgamates the advantages of FEM and DEM. FEM excels in precisely capturing non-uniform tire loads imparted onto the asphalt pavement surface, while DEM affords the means to delve into the internal responses of the heterogeneous asphalt mixture at the particle scale.

Consequently, our proposed coupling method unveils a groundbreaking avenue for micro-mechanical scrutiny of asphalt mixtures under the influence of authentic tire loads. This, in turn, not only augments our understanding of the complex mechanisms of asphalt mixture deterioration under tire loads but also holds the potential to enrich the conceptualization and refinement of asphalt pavement surface design.

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