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Discrete Element Modeling of Void Content Influence on Asphalt–Wheel Interaction

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Abstract— This study investigates the influence of void content on asphalt–wheel interaction using the Discrete Element Method (DEM). A three-dimensional asphalt pavement model, consisting of mineral aggregates (99.5%) and recycled glass (0.5%), was developed to evaluate four void contents (0%, 10%, 15%, and 20%). Contact forces, including adhesive, normal, and tangential components, were analyzed to assess the mechanical response of the pavement. The results show that increasing void content modifies the contact behavior by increasing force fluctuations and energy dissipation while reducing structural stability at high porosity levels. Although higher void contents may promote vibration damping and contribute to noise reduction, excessive porosity compromises mechanical performance. These findings demonstrate that void content is a critical design parameter for balancing mechanical stability and acoustic performance in sustainable asphalt pavements.

Keywords— Discrete Element Method (DEM); asphalt mixture; void content; tire–road interaction; contact forces; porous asphalt; noise reduction; recycled materials

I. Introduction

Asphalt mixtures constitute a critical component of modern transportation infrastructure, with their performance governed by a complex interaction between material composition, internal structure, and loading conditions, [1]. Traditionally, asphalt mixture design has been primarily focused on ensuring adequate mechanical strength, durability, and resistance to environmental degradation. However, recent advancements in pavement engineering have shifted attention toward multifunctional performance, including sustainability, energy efficiency, and environmental impact mitigation. In this context, the incorporation of recycled materials and the optimization of internal structure, particularly void content, have emerged as key research directions.

The internal structure of asphalt mixtures, including aggregate arrangement, binder distribution, and void configuration, plays a decisive role in determining their macroscopic behavior. Numerical methods, especially the Discrete Element Method (DEM), have proven highly effective in capturing these micromechanical interactions. For instance, in paper. [2] was demonstrated that DEM can successfully simulate the internal structure of asphalt mixtures with high tire rubber content, highlighting the influence of particle morphology and composition on force transmission and mechanical response. Similarly, advanced coupled approaches such as FEM–DEM have enabled multiscale analysis of tire–asphalt interaction, providing detailed insight into stress distribution and contact mechanisms under rolling loads, [1], [3]. These methods complement traditional finite element analyses, which, although effective at the continuum scale, often fail to capture the role of granular interactions and evolving contact networks.

At the interface between tire and pavement, the distribution of normal and tangential forces governs not only structural performance but also rolling resistance and energy dissipation. Early investigations. [4] emphasized the importance of accurately characterizing tire–road contact stresses for pavement design. However, such approaches typically assume homogeneous material behavior, thereby neglecting the heterogeneous and discontinuous nature of asphalt mixtures. In contrast, DEM-based modeling allows for explicit representation of particle-scale interactions, including the formation and evolution of force chains, which are essential for understanding load transfer and energy dissipation mechanisms.

In parallel with developments in modeling techniques, significant efforts have been made to enhance asphalt mixtures through the use of recycled and functional materials. The incorporation of fibers, for example, has been widely studied for its ability to improve mechanical stability, crack resistance, and durability, [5]. Likewise, the use of recycled tire rubber has attracted considerable interest due to its environmental benefits and its role in mixture performance. Studies have shown that rubber-modified asphalt mixtures exhibit improved damping capacity, enhanced resistance to environmental loading, and in some cases, self-healing properties, [6], [7]. These improvements are closely related to modifications in the internal structure and porosity of the mixture, which influence both mechanical behavior and energy dissipation.

Among the various design parameters, void content is particularly significant, as it directly affects density, permeability, and internal stress distribution. Increasing porosity alters the contact network between aggregates, leading to more heterogeneous force transmission and enhanced energy dissipation. The authors of scientific paper [8] demonstrated that carefully designed asphalt mixtures with controlled porosity can achieve improved functional performance in urban environments without significantly compromising structural integrity. However, excessive void content may reduce load-bearing capacity and durability, highlighting the need for optimized mixture design.

In addition to its mechanical implications, porosity also plays an important role in the acoustic performance of asphalt pavements. Porous asphalt mixtures, characterized by interconnected void networks, allow sound waves to penetrate into the material, where they are attenuated through mechanisms such as viscous losses, scattering, and internal friction. Experimental studies have confirmed that increasing void content enhances sound absorption and reduces traffic noise levels, [9]. Furthermore, advanced configurations such as double-layer porous asphalt have been shown to provide superior noise reduction performance by optimizing pore structure at multiple scales, [10], [11]. The incorporation of recycled and functional materials can further enhance these effects, as demonstrated in [12], reporting improved noise reduction characteristics in porous drainage asphalt mixtures incorporating sustainable components.

Despite the extensive research conducted on asphalt mixtures, there remains a limited understanding of the micromechanical relationship between void content, force transmission, and tire–asphalt interaction. In particular, the role of void structure in governing normal and tangential force evolution and its connection to energy dissipation mechanisms is not fully captured by conventional approaches. Therefore, the present study applies an established Discrete Element Method (DEM) framework to investigate the influence of void content on asphalt–wheel interaction in asphalt mixtures containing recycled glass. The main contribution of this work is a comparative micromechanical analysis of how variations in void content affect adhesive, normal, and tangential contact forces, thereby providing additional insight into the behavior of this type of asphalt mixture.

II. BIBLIOMETRIC ANALYSIS AND RESEARCH GAP IDENTIFICATION

The bibliometric analysis performed using the Web of Science database highlights the novelty of the present study through a progressive refinement of the search strategy. An initial broad query combining *"asphalt mixture"* OR *"porous asphalt"* resulted in 21,799 publications, confirming that this research area is well established. Similarly, individual searches for *"porosity"* (289,565 results), *"recycled material" OR "reclaimed asphalt pavement"* (91,889 results), and *"Discrete Element Method" OR "DEM"* (86,671 results) indicate that these topics have been extensively investigated independently. However, when these concepts are combined using the Boolean expression:

("asphalt mixture" OR "porous asphalt") AND ("recycled material" OR "reclaimed asphalt pavement") AND (porosity) AND ("Discrete Element Method" OR DEM), only 2 publications are identified. This sharp reduction demonstrates that the combined investigation of asphalt mixtures, void content, recycled materials, and DEM-based modeling remains largely unexplored in the existing literature.

Therefore, the present study addresses this gap by analyzing the influence of void content on asphalt–wheel interaction using the Discrete Element Method, providing a novel micromechanical perspective that links internal structure with contact behavior and overall performance.

A bibliometric analysis was further conducted using VOSviewer based on the Web of Science dataset obtained from the Boolean query: ("asphalt mixture" OR "porous asphalt") AND ("Discrete Element Method" OR DEM)

This search resulted in a total of 489 publications, which were used to construct co-occurrence and network maps of keywords.

The number of articles is much reduced if we apply an investigation by associating the terms "porous asphalt" and "tire".

III. MATERIALS AND METHODS

A numerical investigation based on the Discrete Element Method (DEM) was conducted to evaluate the influence of void content on the mechanical response of asphalt under wheel interaction. The simulations were performed using Rocky DEM (version 2022 R2)

The geometric model (Figure 1) was developed using ANSYS SpaceClaim. A rectangular domain representing the asphalt layer was defined with dimensions:

- Length: 2000 mm
- Width: 500 mm
- Height: 40 mm.

This value is characteristic of the usual average thickness of the road wear layer resulting in a total volume V=0.04 m^3.

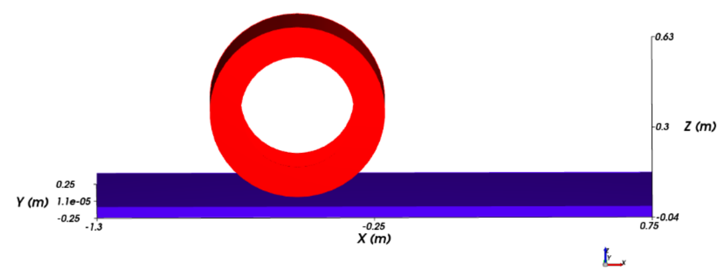

Fig. 1: Geometrical model
Source: Created by the authors

The granular asphalt mixture was modeled using two types of spherical particles: **aggregates**: density: 2600 kg/m³ and diameter: 8 mm, **crushed glass particles**: density: 2700 kg/m³, diameter: 5 mm. The mixture composition was defined based on volume fractions: aggregates: 99.5%, glass: 0.5%. As can be seen, a modified structure of the asphalt mixture was adopted, which involves the use of glass resulting from recycling.

Four different void configurations were analyzed: 0% (reference case), 10%, 15%, and 20%.

The void content n was introduced by reducing the solid volume fraction according to:

$$V_s=(1-n)\cdot V \quad (1)$$

where V_s represents the volume occupied by particles, and V is the total domain volume.

The total mass of particles for each case was computed based on the material densities and corresponding volumetric fractions. The volume of each constituent was calculated as:

$$V_{agg} = 0.995 \cdot Vs \quad (2)$$

$$V_{glass} = 0.005 \cdot Vs \quad (3)$$

where V_{agg} is the volume occupied by aggregate, V_{glass} is the volume occupied by glass particles, Vs is the solid volume.

The mass of each component was then determined by multiplying the density by the occupied volume (Table I).

Table I. Mass of components

Void Content	Solid Volume (m³)	Aggregates (kg)	Glass (kg)
0%	0.040	103.48	0.54
10%	0.036	93.13	0.49
15%	0.034	87.96	0.46
20%	0.032	82.78	0.43

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The calculated masses were introduced into the DEM domain using controlled particle insertion. The material densities and particle sizes were kept constant for all simulations, ensuring that the only varying parameter was the void content (Figure 2).

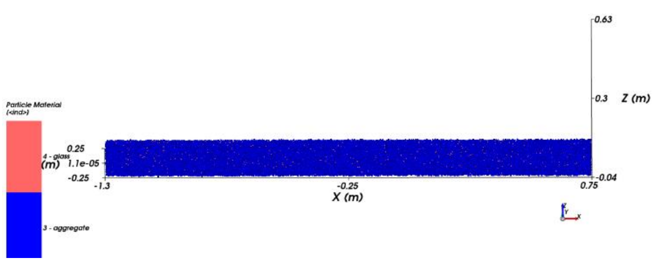

Fig. 2: The distribution of aggregate and glass particles
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A consistent contact model was applied across all cases, and the particle interactions were governed by normal, tangential, and adhesive forces. This approach ensured that differences in mechanical response were solely attributed to variations in internal structure due to void content.

The adopted DEM formulation follows the standard contact models implemented in Rocky DEM. The normal contact interaction is described using the Hysteretic Linear Spring model, while tangential interactions are represented by the Linear Spring Coulomb Limit model, and adhesion is modeled using a constant adhesion law, [13]. These models have been successfully employed in our previous investigations of asphalt-related DEM simulations [13] and [14], ,where the friction and restitution coefficients were experimentally determined through angle-of-repose and shear-angle tests and subsequently verified by calibration simulations before being adopted in the numerical model. The same parameter selection philosophy was applied in the present work to ensure physically representative particle interactions.

Modeling Assumptions

- Particles were assumed to be spherical for computational efficiency
- Material properties were considered constant throughout the simulations
- The glass content was uniformly distributed within the aggregate matrix
- The contact detection parameters were kept constant for all cases

The interaction between particles, filler/bitumen, and the tire is characterized through a set of contact parameters, including the static friction coefficient (particle–particle and particle–tire), the dynamic friction coefficient (particle–particle and particle–tire), the rolling resistance coefficient (associated with particle motion), and the restitution coefficient governing particle collisions. The interaction parameters used in the simulations are summarized in Table II. The coefficient of rolling friction is about 1/30 ∼ 1/20 times of static friction, [15].

Adhesive forces play a crucial role in DEM simulations by governing the interaction mechanisms between asphalt concrete constituents (aggregates and filler/bitumen in the solid state) during their displacement under tire loading.

The adhesive force can be interpreted as a numerical representation of the binder phase, capturing the cohesive interactions within the mixture of aggregates and filler/bitumen in the solid state, [13].

The contact parameters adopted in this study were selected based on both published literature and the authors' previous experience with DEM simulations applied to asphalt engineering. Previous studies by the authors investigated the behavior of asphalt milling equipment [13] and the movement of aggregates in the asphalt plant drying units [14], providing practical guidance for selecting interaction parameters representative of mineral aggregates used in asphalt technology. These parameters were further complemented with literature data concerning tire–particle interaction and recycled glass particles.

Table II. Interaction parameters

Contact pair	Static friction coefficient	Dynamic friction coefficient	Restitution coefficient	Source
Aggregate – Aggregate	0.6	0.6	0.3	[14]
Aggregate – Tire	0.8	0.8	0.3	[16]
Aggregate – Glass	0.5	0.5	0.58	[17]
Glass – Glass	0.16	0.16	0.92	[17]

Source: Created by the authors

Although no experimentally calibrated DEM parameters are currently available for asphalt mixtures containing recycled glass, the adopted values are consistent with published data for materials exhibiting similar mechanical and tribological behavior. Consequently, the model is intended to provide a robust comparative assessment of the influence of void content rather than an absolute prediction of tire–asphalt interaction forces

The elastic behavior of the particles and the tire was defined using Young's modulus and Poisson's ratio (Table III).

Table III. Mechanical properties of materials Source: Created by the authors

Material	Young's Modulus	Poisson's Ratio	Density (kg/m³)	Source
Aggregate	60 GPa	0.25	2600	[18]
Glass particles	70 GPa	0.22	2700	[19]
Tire (rubber)	2 MPa	0.49	1800	[20]

Model limitations.
The objective of the present DEM model is to provide a comparative analysis of the influence of void content on asphalt–wheel interaction under identical simulation conditions. Consequently, all material properties, contact parameters, and loading conditions were kept constant, while void content was considered the only independent variable. Although the adopted parameters were selected from validated literature sources, the model has not yet been calibrated against dedicated experimental measurements for asphalt mixtures containing recycled glass. Therefore, the results should be interpreted as providing qualitative and comparative trends rather than absolute predictions of tire–asphalt interaction. Experimental validation and comparison with coupled FEM–DEM simulations will be the subject of future work.

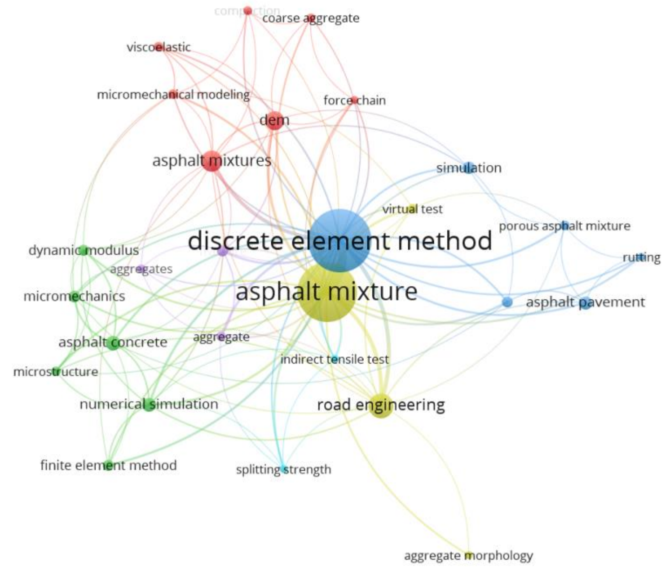
IV. Results and Discussion

A. Bibliometric Results and Research Gap Analysis

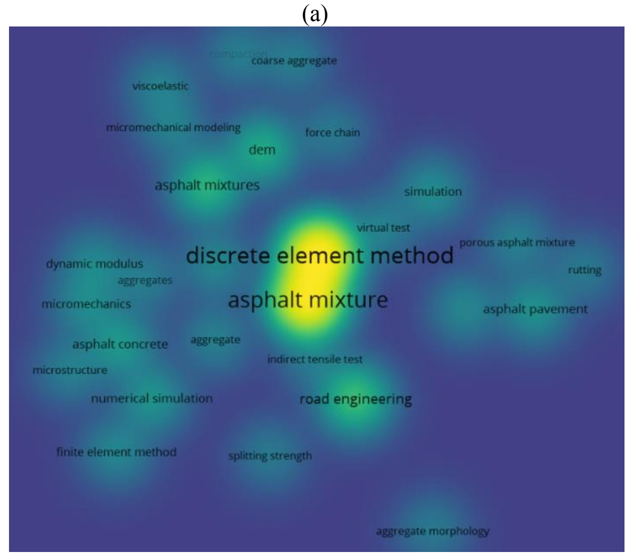
Figure 3a presents the keyword co-occurrence network obtained from the bibliometric analysis performed using VOSviewer, highlighting the main research directions and their interconnections within the field of asphalt mixtures and Discrete Element Method (DEM) applications.

It can be observed that *"asphalt mixture"* and *"discrete element method"* constitute the central nodes of the network, indicating their dominant role and strong interconnection within the literature. These terms act as bridges between multiple research clusters, confirming that DEM is increasingly used to investigate the internal structure and behavior of asphalt mixtures.

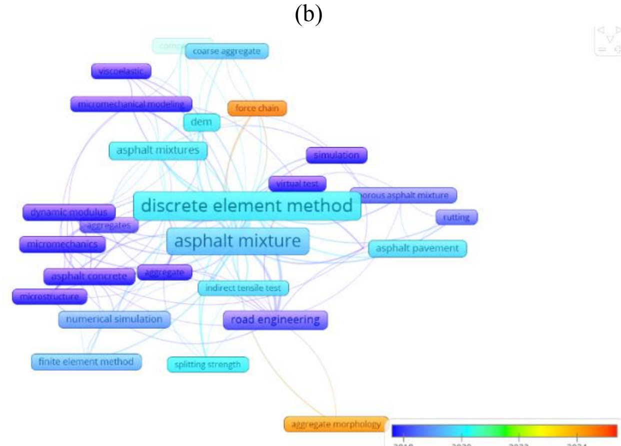
Importantly, although *"porous asphalt mixture"* appears within the network, its relatively weak connectivity compared to the central nodes indicates that porosity-related studies are not strongly integrated with DEM-based micromechanical modeling. Moreover, terms related to *void content* and *tire–pavement interaction* are either absent or weakly represented, highlighting a clear gap in the literature. This observation supports the novelty of the present study, which aims to bridge these domains by investigating the influence of void content on asphalt–wheel interaction using a DEM-based approach.



(a)



(b)



(c)

Fig. 3: VOSviewer results: (a) Co-occurrence map of author keywords; (b) Density visualization of the keyword co-occurrence network; (c) Temporal overlay visualization of author keywords
Source: Created by the authors

The temporal evolution map presented in Figure 3c provides additional insight into how research trends in asphalt mixtures and Discrete Element Method (DEM) applications have developed over time. In this visualization, the color scale (ranging from blue to red) represents the average publication year of each keyword, allowing the identification of emerging and mature research topics.

This observation highlights a clear research gap, as current studies tend to investigate micromechanical behavior or porous asphalt performance separately, without fully integrating these aspects within a unified DEM-based framework. Therefore, this study addresses this gap by applying DEM to analyze the combined influence of void content and recycled glass on asphalt–wheel interaction, an area that has received limited attention in the existing literature.

B. DEM results

Figure 4 illustrates the tire imprints formed on the asphalt surface during the simulation, providing a visual representation of the contact and deformation process.

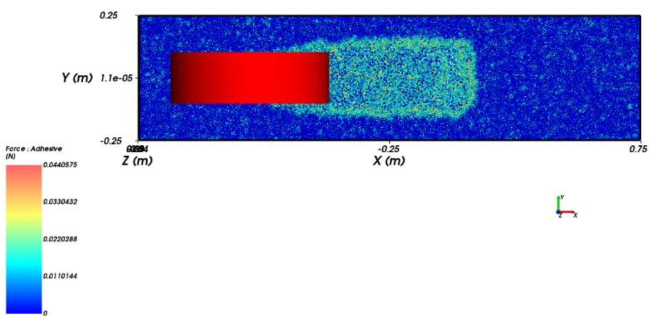


Fig. 4: Tire Imprints
Source: Created by the authors

Figure 5, Figure 6, and Figure 7 illustrate the evolution of the maximum adhesive, normal, and tangential forces acting on particles for different void contents. These parameters were selected as they provide a comprehensive description of the micro-mechanical behavior of the system, capturing the cohesive interactions (adhesive forces), load transfer mechanisms (normal forces), and frictional resistance (tangential forces) within the granular asphalt structure.

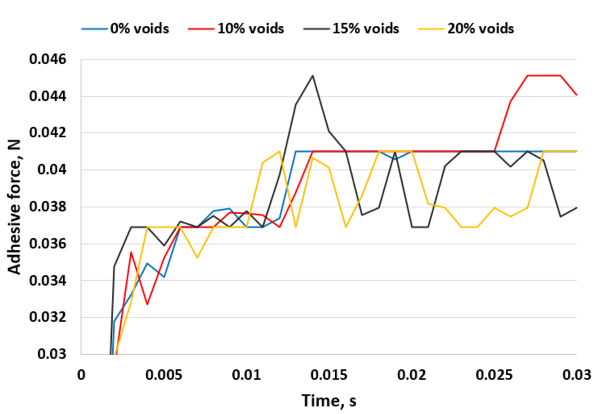


Fig. 5: Evolution of maximum adhesive force
Source: Created by the authors

From Figure 5 it can be observed that all cases exhibit an initial increase in adhesive force, followed by a transition toward a quasi-stationary regime; however, the magnitude and stability of this regime are strongly influenced by the void content. In case of a fully dense structure (0% voids), the adhesive force stabilizes at approximately 0.041 N with minimal fluctuations, indicating a continuous and rigid contact between the tire and the surface. Such behavior is typically associated with efficient transmission of vibrational energy, which in turn contributes to higher levels of noise radiation.

As the void content increases to 10%, the adhesive force reaches slightly higher peak values, approaching 0.045 N, while maintaining moderate variability. This suggests that although the contact remains relatively strong, localized discontinuities begin to emerge, potentially offering a limited degree of energy dissipation. Consequently, this configuration may represent a compromise between maintaining adequate adhesion and achieving partial noise reduction. A more pronounced change is observed at 15% voids, where the adhesive force exhibits significant fluctuations characterized by frequent peaks and drops. This behavior reflects continuous particle rearrangements and intermittent contact conditions within the granular structure, which enhance energy dissipation mechanisms. From an acoustic perspective, such instability is beneficial, as it reduces the coherence of vibration transmission and thereby contributes to noise attenuation.

When the void content reaches 20%, the adhesive force decreases in magnitude and becomes more dispersed, indicating a softer and less consistent contact interface. This condition enhances the material's capability to absorb vibrational energy, leading to the most effective noise reduction among the analyzed cases. However, this improvement in acoustic performance is accompanied by a reduction in mechanical stiffness and potentially diminished tire grip.

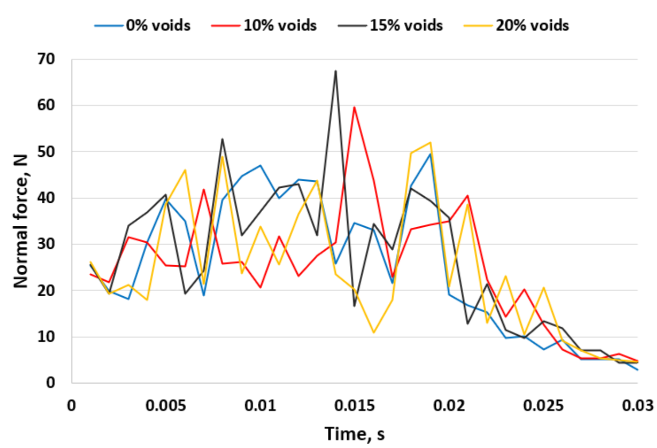


Fig. 6: Evolution of maximum normal force
Source: Created by the authors

Regarding the evolution of maximum normal force (Figure 6), all cases exhibit a highly dynamic response, with significant fluctuations in the normal force, particularly during the initial and intermediate stages of contact. This behavior reflects the inherently discontinuous nature of granular systems, where load transfer occurs through evolving networks of particle contacts. In case of a dense structure (0% voids), the normal force reaches moderate peak values, generally below 50 N, and exhibits relatively smoother variations compared to higher void contents, indicating a more stable and uniformly distributed contact network. As the void content increases to 10%, the normal force becomes more irregular, with higher local peaks approaching 60 N, suggesting that the load is transmitted through fewer contact chains, leading to localized stress concentrations. A more pronounced effect is observed at 15% voids, where the highest peaks, exceeding 65 N, are recorded; this indicates the formation of strong but transient force chains that intermittently carry a large portion of the load before collapsing and reforming, a behavior typical of granular systems with increased porosity. When the void content reaches 20%, the normal force remains highly fluctuating but shows a general decrease in sustained high values, particularly in the later stages, reflecting a weakened and less stable contact structure. From a tribological and acoustic perspective, these results suggest that increasing void content enhances energy dissipation through intermittent contacts and force chain instability, which contributes to vibration damping and noise reduction, although at the expense of reduced load-bearing capacity and contact stability.

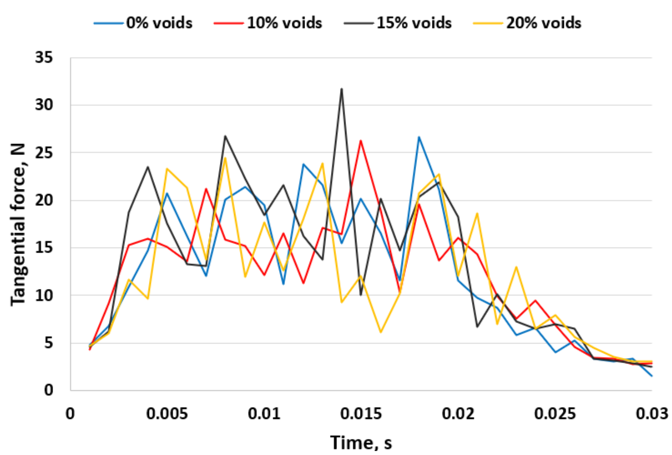


Fig. 7: evolution of maximum tangential force
Source: Created by the authors

Similar to the normal force response, in the case of tangential force (Figure 7), all cases exhibit pronounced fluctuations over time, reflecting the intermittent nature of particle contacts and the continuous rearrangement of the granular structure. However, the tangential force, which is directly associated with frictional resistance and energy dissipation, shows a slightly lower magnitude and a more irregular pattern compared to the normal force.

In case of a dense structure (0% voids), the tangential force reaches peak values of approximately 25–27 N and exhibits relatively smoother variations, indicating a more stable frictional interaction governed by persistent contact points. This stability suggests a more uniform shear transfer, which can promote coherent vibration transmission and, consequently, higher noise levels. As the void content increases to 10%, the tangential force becomes more variable, with peaks around 25–26 N and noticeable fluctuations, indicating the onset of localized slip events and partial loss of contact continuity

A more pronounced behavior is observed at 15% voids, where the tangential force exhibits the highest variability and peak values exceeding 30 N. This indicates the formation and collapse of strong frictional force chains. At 20% voids, although the peak tangential forces remain significant, the overall response becomes more dispersed and less sustained, reflecting a weaker and more unstable contact network.

From the perspective of vibration and noise generation, the amplitude of the tangential force fluctuations plays a critical role. Larger and more irregular amplitudes, as observed particularly in the 15% and 20% void cases, indicate enhanced energy dissipation and reduced coherence of the excitation signal transmitted to the tire structure. Consequently, higher void contents are associated with lower effective vibration amplitudes and improved noise attenuation. Conversely, the more stable and less fluctuating tangential force observed at 0% voids suggests a more coherent excitation mechanism. This leads to higher vibration amplitudes and potentially increased noise radiation.

These findings are consistent with the observations reported by [12], who demonstrated that porous asphalt mixtures with higher void ratios exhibit superior sound absorption and noise reduction performance. In their study, the enhanced acoustic behavior was attributed to the high porosity of the material, which allows incident sound waves to penetrate into the internal structure, where they are progressively attenuated through multiple reflections, viscous losses, and energy dissipation within the interconnected void network. Article [9] indicates that excessive air void content does not significantly improve pavement noise reduction, recommending a maintained range of 17%–24%. This optimal range is suggested for effective, balanced acoustic performance without diminishing returns. Similarly, research [11] indicates that a porosity of approximately 22% is particularly effective at mitigating high-frequency noises, while the use of relatively fine aggregate—specifically a Nominal Maximum Aggregate Size of 9.5 mm—targets low-frequency noise components. The study further established that once porosity increases beyond 20%, the gains in acoustic performance diminish.

V. CONCLUSION

The use of DEM offers the perspective of structural modeling of asphalt pavements with complex composition, including using recycled materials.

The results of the analysis provide insights into he effect of the interaction between the vehicle tire and the asphalt pavement. The present modeling is preliminary and brief It was aimed at demonstrating the effectiveness of using DEM in the study of the interaction of the tire with the asphalt layer, under conditions of a diversified composition of the asphalt mixture.

From the perspective of the forces developed during the interaction of the tire with the asphalt, it is found that porosity plays an essential role in the homogenization of the response to the pressure exerted by the tire. High values of the void volume led to an attenuated amplitude of the forces - adhesion, tangential, and normal - and to an increase in the frequency of the dynamic response, which has consequences on the uniformization and stabilization of the extreme instantaneous values. These results suggest that increasing void content promotes mechanisms associated with greater energy dissipation and vibration damping. According to previous experimental studies, such mechanisms may contribute to improved tire–road noise attenuation. Nevertheless, acoustic performance was not directly evaluated in the present study, and this interpretation should therefore be regarded as indirect. From the perspective of vibration and noise generation, the amplitude of the tangential force fluctuations plays a key role. Larger and more irregular amplitudes, as observed especially in the cases of 15% and 20% voids, indicate increased energy dissipation and reduced coherence of the excitation signal transmitted to the tire structure. Consequently, higher void contents are associated with lower effective vibration amplitudes and improved noise attenuation. In contrast, the more stable and less fluctuating tangential force observed at 0% voids suggests a more coherent excitation mechanism, leading to higher vibration amplitudes and potentially increased noise radiation.

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