INSTITUT NATIONAL DES SCIENCES APPLIQUÉES STRASBOURG

PhD proposal INSA Strasbourg

PhD subject: Hybrid DEM-AI Simulations for the Study of Infrastructure Resilience under Climate Change Hazards.

Abstract:

In the context of the increasing impacts of climate change on transport infrastructure, this research aims to model the behavior of road structures subjected to extreme climatic conditions, with particular emphasis on the effect of high temperatures on their durability. The study is based on a multi-scale hybrid numerical simulation approach combining Contact Dynamics (DEM/CD) and Artificial Intelligence (AI) surrogate modeling, to analyze the viscoelastic behavior of bituminous materials and to identify damage mechanisms within surface layers. Simulations will be performed using the LMGC90 code, incorporating a viscoelastic contact law calibrated from experimental data obtained within the ANR Binary project (2020–2025). This approach will enable the characterization of intergranular forces, stress distribution, and critical zones of rutting and particle detachment, with the objective of developing predictive models of wear and degradation of surface layers under extreme climatic conditions, supported by multi-scale and full-scale experimental testing.

Project Challenges:

Transport infrastructure constitutes a fundamental pillar of the economic and social functioning of territories. Their accelerated degradation due to climate change leads to increased risks for user safety, higher maintenance costs, and disruptions to mobility services. By proposing modeling tools capable of anticipating pavement damage under extreme climatic conditions, this project contributes to improving the durability of road infrastructure, optimizing maintenance strategies, and reducing associated public costs. It thus addresses major challenges related to territorial resilience, road safety, and sustainable infrastructure management.

Climate change induces intensified thermal and mechanical stresses on pavements, often exceeding the assumptions considered during their design. Extreme temperatures, more pronounced thermal cycles, and intense climatic events accelerate mechanisms such as rutting, cracking, and surface layer degradation. This project is part of an adaptation strategy to climate change, aiming to better understand and predict the behavior of bituminous materials under extreme conditions, to design more robust, durable, and climate-adapted road structures.

From a scientific perspective, the project lies at the intersection of granular mechanics, the rheology of bituminous materials, and multi-scale numerical simulation. It aims to advance the state of the art by developing and validating innovative hybrid numerical models coupling discrete approaches and AI, incorporating viscoelastic contact laws capable of capturing temperature and loading effects. Identifying damage mechanisms at the micromechanical scale and linking them to the macroscopic response of road structures represents a major scientific contribution, paving the way for new predictive tools for pavement design and assessment under extreme climatic conditions.

The main objective of this project is to analyze the influence of exceptional events induced by climate change on the mechanical performance and degradation mechanisms of road materials, with particular focus on the effect of extreme temperatures. Numerical tools developed within the research team, such as the Discrete Element Method (DEM) coupled with surrogate AI models, will be used to model pavement behavior. These approaches will allow analysis from the particle scale to the global scale of material performance and potential disorders, such as rutting and surface cracking, under extreme environmental conditions. Experimental methods, including triaxial tests equipped with a heating cell, will be implemented to validate and calibrate the numerical modelss. The results of this study will contribute to integrating extreme natural events into long-term degradation predictive models, particularly for rutting and particle detachment, to be incorporated into pavement design.

Prerequisites:

This topic requires competencies in numerical simulation (DEM and/or FEM), continuum mechanics, constitutive laws of construction materials, and structural modeling. Basic knowledge of the Python programming language applied on AI would be an asset. The candidate must hold a master's degree in computational mechanics, civil engineering, or computer science, or a related field, with solid experience in scientific computing, numerical methods, or physics-informed simulations.

Resources and Environment:

Upon arrival, the doctoral candidate will be welcomed, together with other new PhD students, by the research unit management, who will introduce the teams and scientific themes developed within the laboratory. Throughout the three-year doctoral program, the candidate will attend the unit's scientific seminars and Master's-level courses as part of research-based training.

During the entire doctoral period, the candidate will participate in GC-E team seminars, individual thesis monitoring committees, and scientific events organized by the Research Directorate of INSA Strasbourg and the Mechanics Department of the ICube laboratory, where they will present the progress and results of their work. They will also disseminate their research at national conferences and international congresses.

The support provided by the research unit will follow a progressive approach, both scientifically and personally, throughout the doctoral journey. The candidate will benefit from the material and human resources made available by the GC-E team for numerical modeling, including appropriate computing equipment, software tools, and local scientific supervision in numerical methods.

Detailed subject:

Climate change, through consequences such as global warming, sea-level rise, prolonged drought periods, and increased frequency of floods and intense storms, represents a major threat to buildings and infrastructure. Heavy rainfall events and exceptional flooding cause erosion and degradation of materials constituting roads and railways. Moreover, global warming intensifies temperature variations, exposing pavement materials to thermal conditions exceeding those considered during design. Existing research solutions remain incomplete and do not always allow anticipation of the worsening or emergence of new effects associated with ongoing climate change. It is therefore essential to explore and evaluate innovative approaches to protect buildings and structures from climate change and natural hazards.

The primary objective of this work is to model the behavior of road structures subjected to extreme climatic conditions, particularly high temperatures, through a campaign of numerical simulations. The resulting numerical data will enable identification of intergranular resistance under shear and tensile loading within surface layers, with the aim of establishing predictive damage models for structural design under extreme conditions.

Numerical simulations will be carried out using the Contact Dynamics (CD) method applied to rigid particles. This method relies on a discrete approach for simulating the dynamics of irregular granular media [1]. The LMGC90 software will be used, allowing the modeling of assemblies of rigid or deformable particles with various shapes through different algorithms [2]. To represent bituminous material behavior, a viscoelastic contact law has been implemented. The developed contact model combines the original CD formulation for rigid particles, ensuring non-penetration conditions, with a viscoelastic model acting on distant contacts. For the viscoelastic component, the VENoL model [3] will be used; which is capable of reproducing the viscoelastic behavior of bituminous materials. Current work at the ICube laboratory (INSA Strasbourg) demonstrates that this contact law accurately reproduces rheological properties such as the evolution of the complex modulus and phase angle as functions of frequency and temperature [3-6] (cf. Fig. 1).

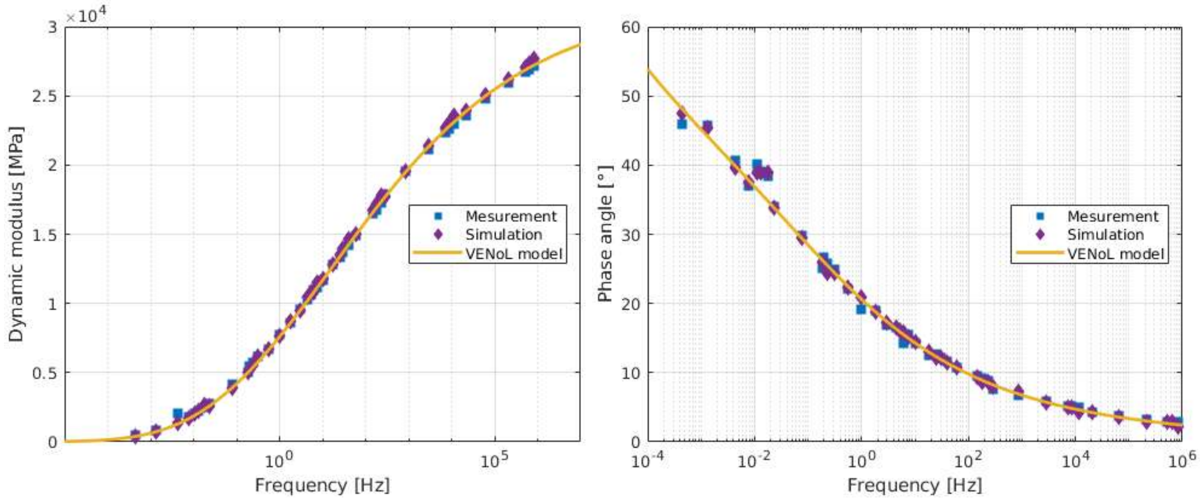

Fig. 1: Master curves of the complex modulus obtained from experimental tests and numerical simulations for a two-point bending (2PB) complex modulus test configuration, for different particle shapes (T_ref = 15 °C), and comparison with the VENoL model: (a) Magnitude of the complex modulus. (b) Phase angle [4].

To analyze behavior under extreme temperatures, viscoelastic contact law parameters will be calibrated using master curves of these materials. Subsequently, based on the Time–Temperature Superposition Principle (TTSP), these parameters will be extrapolated to extreme temperature conditions and integrated into a multi-scale FEM/DEM model implemented in LMGC90 [7, 8].

In this framework, the surface layer will be simulated using Contact Dynamics with a viscoelastic contact model, while base and sub-base layers will be modeled using FEM. This modeling will be accelerated using an AI surrogate approach [9], where the numerical results will be used to train a Machine Learning (ML) algorithm to predict the viscoelastic interactions between particles and also at the tire-pavement contact level [10]. Traffic loading will be represented by a force field reproducing the tire-pavement contact footprint.

Measurement of inter-particle forces will allow identification of stress distributions at the macroscopic scale within pavement layers. At the micromechanical scale, this approach will enable identification of critical zones prone to rutting and surface cracking. These results will support the development of predictive models for wear and damage, particularly related to rutting and particle detachment.

To achieve these objectives, the study will initially rely on experimental tests results obtained by the ANR Binary project (2020–2025), in collaboration with INSA Strasbourg and Gustave Eiffel University (Nantes). These tests involve bituminous materials and have been carried out at multiple scales, from microscopic tests (Rulob) to laboratory structural tests such as WTT (Wheel Tracking Test) and T2R (Triboroute braking/acceleration).

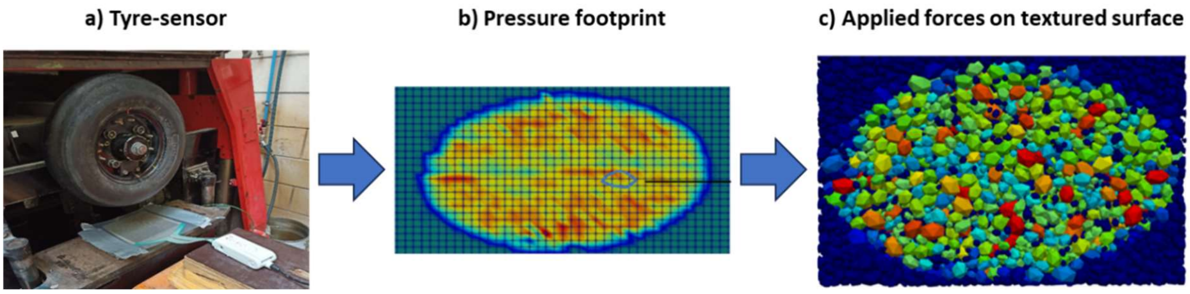

Fig. 2: Schematic representation of the tire–sensor–CD coupling chain, including the application of contact forces on a textured surface. (a) Measurement of tire–sensor (pressure). (b) Construction of the force matrix from pressure footprint data. (c) Application of vertical forces to the particle surfaces in the Contact Dynamics simulation [6].

References:

[1] Radjai, F., & Richefeu, V. (2009). Contact dynamics as a non-smooth discrete element method. Mechanics of Materials, 41(6), 715-728.

[2] F. Dubois and M. Jean, The non-smooth contact dynamic method: recent lmgc90 software developments and application. In: Analysis and Simulation of Contact Problems. Springer, 2006. p. 375-378.

[3] Coulon, L., Koval, G., Chazallon, C., & Roux, J. N. (2021). Analytical modelling of thixotropy contribution during T/C fatigue tests of asphalt concrete with the VENoL model. Road Materials and Pavement Design, 22(sup1), S536-S559.

[4] Ge, H., Quezada, J. C., Le Houerou, V., Chazallon, C., & Hornych, P. (2023). A new tire-sensor-pavement coupling chain for investigating asphalt mixture responses under rolling tire loads. Road Materials and Pavement Design, 24(sup1), 245-262.

[5] Ge, H., Quezada, J. C., Le Houerou, V., & Chazallon, C. (2021). Three-dimensional simulation of asphalt mixture incorporating aggregate size and morphology distribution based on contact dynamics method. Construction and Building Materials, 302, 124124.

[6] Quezada, J. C., Hammoud, O., Liu, D., Hammoum, F., Chazallon, C., Klein, P., & Cesbron, J. (2025). Advanced discrete element analysis of tyre–pavement interactions on textured bituminous surfaces based on the French wheel tracking test. Road Materials and Pavement Design, 26(sup1), 481-502.

[7] Bagnéris, M., Dubois, F., Jean, M., Martin, A., Taforel, P., & Visseq, V. (2013). High performance hybrid FEM/DEM simulation tool for numerical analysis of historical structures. In Digital Heritage International Congress (DigitalHeritage), 2013 (Vol. 1, pp. 537-544). IEEE.

[8] Taforel, P., Renouf, M., Dubois, F., & Voivret, C. (2015). Finite element-discrete element coupling strategies for the modelling of ballast-soil interaction. International Journal of Railway Technology, 4(2), 73-95.

[9] Hadi, A., Moradi, M., Pang, Y. et al. Adaptive AI-based surrogate modelling via transfer learning for DEM simulation of multi-component segregation. Sci Rep 14, 27003 (2024). https://doi.org/10.1038/s41598-024-78455-7

[10] Lu, L., Gao, X., Dietiker, J. F., Shahnam, M., & Rogers, W. A. (2021). Machine learning accelerated discrete element modeling of granular flows. Chemical Engineering Science, 245, 116832.