Homogenization-Driven Acoustic Performance Modeling in Particulate Composites for Noise Mitigation

D. Mačiūnas[1a),*], S. Borodinas[1b)], R. Kačianauskas[1c)], S. Nosewicz[2d)] and R. Stonys[1e)]

[1]Faculty of Civil Engineering, Vilnius Gediminas Technical University, Vilnius, Lithuania
e-mails: a) darius.maciunas@vilniustech.lt, b) sergejus.borodinas@vilniustech.lt,
c) rimantas.kacianauskas@vilniustech.lt, e) rimvydas.stonys@vilniustech.lt

[2]Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland
e-mail: d) snosew@ippt.pan.pl

KEYWORDS: *Multiscale Modeling, Computational Homogenization, Acoustic Wave, Effective Material.*

Lightweight particulate composites (LPCs) are engineered materials that incorporate low-density fillers into cementitious matrices to achieve reduced weight, improved thermal insulation [1], and enhanced acoustic properties [2]. When embedded in calcium aluminate cement (CAC) matrices, fly ash cenospheres (FACs) not only lower the composite density, but also introduce controlled porosity, which is critical for noise reduction applications [3].

Accurate prediction of acoustic behavior in such heterogeneous materials remains challenging due to complex microstructures [4], [5] and the high computational cost of detailed simulations [6]. This study proposes a homogenization-driven finite element method (FEM) framework for multiscale modeling of heterogeneous LPC composed of FACs and concrete matrix. The approach accounts for inclusion morphology and spatial distribution while maintaining computational efficiency.

The model links microscale features with macroscale acoustic response, enabling reliable prediction of effective mechanical and acoustic properties. Results show good agreement between heterogeneous simulations and their homogenized equivalents, confirming the validity of the approach. The framework demonstrates strong potential as an efficient design tool for LPC optimization. Future work will include experimental validation and comparison with analytical models.

ACKNOWLEDGEMENT: This research work has received funding from the project "Civil Engineering Research Centre" (agreement No S-A-UEI-23-5, ŠMSM).

[1] D. Mačiūnas, S. Nosewicz, R. Kačianauskas, R. Boris, R. Stonys, Numerical Simulation of Thermal Conductivity and Thermal Stress in Lightweight Refractory Concrete with Cenospheres, *Materials*, **16**(1), p. 190, 2023. https://doi.org/10.3390/ma16010190

[2] Q. Liu, X. Liu, C. Zhang, F. Xin, A Novel Multiscale Porous Composite Structure for Sound Absorption Enhancement, *Compos. Struct.*, **276**, p. 114456, 2021. https://doi.org/10.1016/j.compstruct.2021.114456

[3] H. Xie, Y. Li, E. Kahya, B. Wang, X. Ge, G. Li, Physical Properties and Environmental Impact of Sound Barrier Materials Based on Fly Ash Cenosphere, *Buildings*, **12**(3), 2022. https://doi.org/10.3390/buildings12030322

[4] W. Lee, S. Kim, H. Shin, Accelerated Multiscale Data-driven Finite Element Analysis Using Mean-field Homogenization Method with Knowledge Transfer, *J. Comput. Phys.*, **558**, 2026. https://doi.org/10.1016/j.jcp.2026.114870

[5] A. Elbana A. Khennane, Development of Generalized Yield Surface of Fly Ash Microbubble Composites Using Nonlinear Multiscale Analysis, *Mechanics of Materials*, **212**, 2026. https://doi.org/10.1016/j.mechmat.2025.105532

[6] V. T. Nguyen, V. H. Nguyen, S. Naili, Deep Learning-based Multiscale Prediction of Composite Aerogels' Effective Thermal Conductivity, *Int. J. Mech. Sci.*, **304**, 2025. https://doi.org/10.1016/j.ijmecsci.2025.110617