DOI: 10.61782/fa.2025.0003

FORUM ACUSTICUM EURONOISE 2025

A 3D FINITE ELEMENT MODEL OF ULTRASONIC WAVES TRAVELLING THROUGH PERVIOUS CONCRETE

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ABSTRACT

This study investigates ultrasonic (US) wave propagation in pervious concrete (PeC) through 3D finite element simulations. A simplified geometric model, representing PeC as a series of trimmed-out spheres, is proposed to analyze the relationship between US wave speed and porosity. The numerical results support an analytical model that aligns with existing experimental data, demonstrating a decrease in US speed with increasing porosity. The model incorporates key parameters such as aggregate size, Young's modulus, and density, revealing their impact on wave propagation. While it effectively predicts ultrasonic behavior, certain limitations—such as uniform aggregate size and idealized geometry—suggest directions for future refinement. These findings establish a foundation for ultrasonic PeC assessment, with potential applications in quality control and material characterization.

Keywords: *pervious concrete, ultrasound, wave propagation, numerical modeling, porosity*

1. INTRODUCTION

Pervious concrete (PeC) is a highly permeable material made by mixing Portland cement, coarse aggregates, water, and little to no fine aggregate. Its network of interconnected voids provides high infiltration capacity, making it suitable for sustainable urban drainage applications such as parking lots, sidewalks, and driveways [1,2].

In addition to permeability, mechanical strength is essential for PeC to withstand service loads. Both properties are influenced by porosity, which is controlled by the cement paste-to-aggregate ratio (Pa/Ag). Higher paste content increases strength but reduces porosity and permeability, requiring a balanced design for optimal performance.

While porosity can be measured in laboratories, reliable field tests are necessary for quality control. Ultrasonic (US) wave propagation offers a promising non-destructive method. US waves provide information about internal material characteristics, with recent studies finding negative correlations between US wave speed and PeC porosity. Empirical studies have linked wave speed with porosity and permeability, and some studies suggest combining parameters for improved predictions [4–14], but there are no studies focused on explaining such phenomenon.

With that motivation, and based on our previous studies addressing this matter [13,14], here we present a 3D finite element method (FEM) numerical model of US travelling through PeC. The model manipulates factors such as aggregate size, material properties, and wave characteristics. The study seeks to better understand the relationship between US wave speed and porosity. The findings will support accurate field porosity assessments and enhance PeC evaluation methods.

2. FEM MODEL DESCRIPTION

The FEM model was implemented in COMSOL Multyphysics. It consisted in a line of "trimmed-out-spheres" which may represent a PeC solid medium,

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composed of cement-paste-coated aggregates and air-filled-pores, through which P-waves travel. Waves were generated by exciting one end of the solid and they were sensed at the center of each sphere. The following physical parameters can be configured: Young's elastic modulus E, Poisson's ratio v, density ρ, sphere's nominal diameter D and porosity P. No energy-loss mechanisms were included.

The solid medium's geometry was modeled by aligning up to twelve spheres of nominal diameter D; four domes of height $e/2$ were trimmed out from each sphere, to simulate the contact between the cement-paste-coated aggregates. See Figure 1.

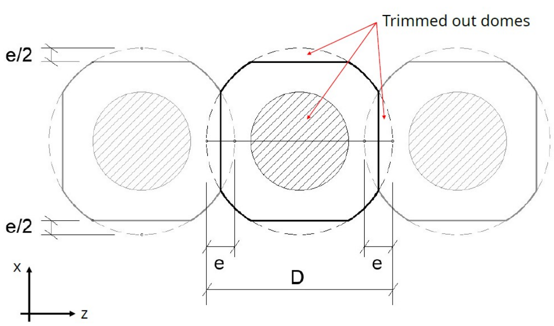

Figure 1. Model's geometry schematics [13].

Using this geometry, porosity P can be obtained by [13]

$$P(\%) = 100\frac{V_{space} - V_{solid}}{V_{space}} \quad (1)$$

where,

$$V_{space} = (D - e)^3 \quad (2)$$

$$V_{solid} = V_{sphere} - 6V_{dome} = \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 - 6\left[\frac{\pi e^2}{12}\left(\frac{3D}{2} - \frac{e}{2}\right)\right] \quad (3)$$

Figure 2 presents a sample geometry implemented in COMSOL Multyphysics. The input force was applied onto the auxiliary disk at z = 0. The lateral surfaces of the spheres were fixed to move at their normal directions, which is compatible with a P-wave in an infinite medium. Additional FEM model details are provided elsewhere [13].

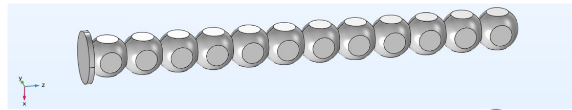

Figure 2. Model's geometry implemented in COMSOL Multyphysics.

MODEL OUTPUTS AND PROCESSING

The raw outputs of the model are the temporal signals (waveforms), one for each virtual sensor. The wave time of flight (ToF) was determined in each waveform using a threshold "Th.", expressed as an amplitude percentage of the waveform's first coherent peak. Each model run's wave speed was obtained as the slope of the resulting ToF series vs. the virtual sensors' positions. The different parameters where varied to analyze how these affect the resulting wave speed, and particularly the wave speed vs. porosity P relationship. By modifying the model's geometry, we were able to obtain the US wave speed for a series of porosity values: 8%, 15%, 23%, 31%, and 40%. Thus, we modified the other model parameters, D, E, and ρ, one at a time, to assess how they influence the US wave speed vs. porosity relationships. To this end, three values of D were assessed, 5 mm, 10 mm, and 20 mm, as well as three values of E, 30 GPa, 45 GPa and 60 GPa, and three values of ρ, 2000 kg/m^3, 2400 kg/m^3 and 2800 kg/m^3. Poisson's ratio ν and the US center frequency f_c were kept constant at 0.2 and 50 kHz, respectively. We also assessed the use of three different thresholds to calculate ToF: 0.1%, 1% and 100% of the waveforms' first coherent peak.

3. MODEL RESULTS

3.1 Waveform results

Figure 3a and 3b present the resulting waveforms of two sample model runs, which differed only in the PeC porosity P, 8% and 40%, respectively.

Note that the waveforms in Figure 3a, with very low porosity (8%), have almost constant amplitude level, shown by the triangular markers. In contrast, Figure 3b, with significantly higher porosity (40%), shows waveforms that diverge more noticeably; there, progressive decrease in the amplitude of the triangles, becoming less negative, indicates clear amplitude attenuation as the wave propagates, even though there is absence of energy-loss mechanisms in the model. This phenomenon may be attributed to dispersive effects.

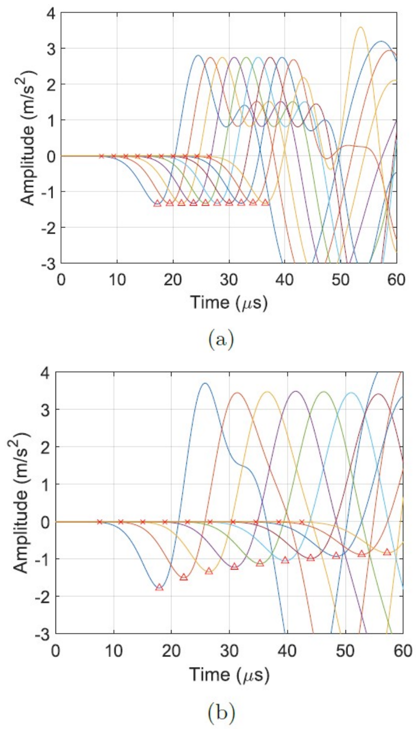

Figure 3. Sample output waveforms using D = 10 mm, E = 30 GPa, ρ = 2400 kg/m^3, and (a) P = 8% and (b) P = 40%. Red crosses indicate the 1% Th. And triangles the 100% Th [13].

3.2 Wave speed vs. porosity, influence of *D* and Th.

Figure 4 presents the simulations results of US wave speed vs. porosity for the model series using E = 30 GPa, and ρ = 2400 kg/m^3, including the three different diameters and three different ToF processing thresholds.

We can see in Figure 4 that for the three cases analyzed, the US wave speed decreases as porosity increases, almost linearly with a slight negative concavity. At low porosity (P = 8%), all curves display wave speed of ~3500 m/s which is consistent with the theoretical P-wave speed, in this case, 3727 m/s (associated to P = 0 %). However, the mean slopes of these curves are not the same: as the diameter D increases, the curves' slopes become less negative. For instance, considering the Th.=1% curves: the D = 10 mm curve's slope is 13 % greater than the D = 5 mm curve's slope; and it grows another 48 % between D = 10 mm and 20 mm.

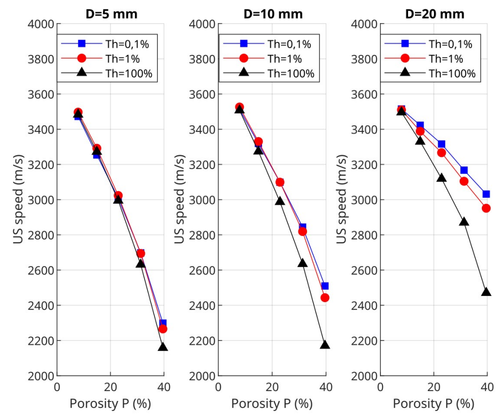

Figure 4. Wave speed vs. porosity for D = 5 mm, D = 10 mm, and D = 20 mm, using three thresholds, with E = 30 GPa, ρ = 2400 kg/m^3.

Another interesting characteristic is that these relationships depend on the selected threshold, but not independently of the diameter. To depict this, note that for D = 5 mm, the three Th. curves overlap, and for D = 10 mm, only the Th. 100 % differs, but the differences among curves are more prominent for D = 20 mm. These differences are due to a dispersive effect in which the wave phases are slowed down as the wave propagates, and thus, yielding different wave speeds results when using different thresholds (because each threshold is associated to different wave phases). Thus, we may assert that, for constant wave's frequency, our signals show that larger diameters produce larger dispersive effects for equal levels of porosity.

3.3 The influence of material parameters E and *ρ*

Figure 5 presents the wave speed vs. porosity resulting relationships for the model series using D = 10 mm, Th. 1 % and varying E and ρ. We selected Th. 1 % as it is an intermediate value, not significantly affected by dispersion, but realistic to extend to experimental signals and avoid capturing noise. As expected, we may see in Figure 5a that increments of E shift the curves upwards, and in Figure 5b, increments of ρ shift the curves downwards. In both cases, these shifts are almost parallel, with similar slope and curvature, indicating a significant independence between the diameter.

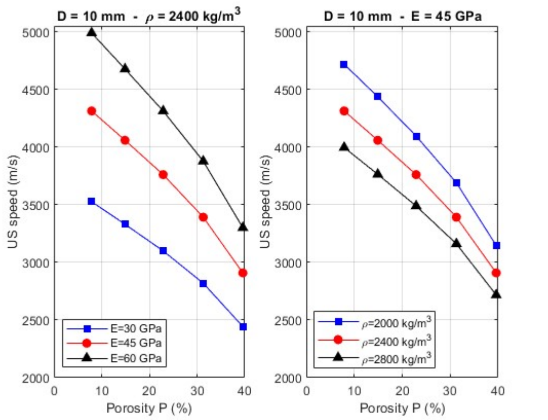

Figure 5. Wave speed vs. porosity for D = 10 mm, and Th. 1 % showing (a) three values of E, and (b) three values of ρ.

4. CONCLUSIONS

This study investigated ultrasonic (US) wave propagation in pervious concrete (PeC) using 3D FEM numerical simulations. We modeled PeC as a series of trimmed spheres, in which the porosity is directly obtained from the geometry, particularly affected by the contact area between spheres. Despite its simplicity, our model may reproduce the overall experimental trends observed by the community, confirming that higher porosity reduces US wave speed.

From our numerical results and analyses, we me conclude that:

- The model aligns with experimental data previously presented by the community as well as theoretical expectations.
- Aggregate size has a significant effect on the slope of the US speed-porosity relationships.
- The wave propagation phenomenon is dispersive, so the method to quantify the wave's time of flight (ToF) may affect the extracted US speed-porosity relationships.
- Young's modulus and density principally produce parallel shifts of the US speed-porosity relationships.

Future work should focus on the model's validation using experimental data, explore advanced wave effects, and compare it to other theoretical porous media models.

5. ACKNOWLEDGEMENTS

The authors would like to thank Dr. Ing. Luis Segura and Ing. Ignacio Marrero for their assistance with the preparation of the pervious concrete specimens. Finally, we would also like to thank the Uruguayan Agency of Research ANII, and the CSIC of Udelar for their support.

6. REFERENCES

[1] ACI Committee 522: Report on Pervious Concrete. American Concrete Institute Farmington Hills, MI, USA (2010).

[2] Tennis, P.D., Leming, M.L., Akers, D.J.: Pervious Concrete Pavements. Portland Cement Association, Skokie, Illinois, and National Ready Mixed Concrete Association, Silver Spring,, Maryland, USA (2004).

[3] Pieralisi, R., Cavalaro, S.H.P., Aguado, A.: Advanced numerical assessment of the permeability of pervious concrete. Cem. Concr. Res. 102, 149–160 (2017).

[4] Amini, K., Wang, X., Delatte, N.: Statistical modeling of hydraulic and mechanical properties of pervious concrete using nondestructive tests. J. Mater. Civ. Eng. 30(6), (2018).

[5] Martins Filho, S.T., Bosquesi, E.M., Fabro, J.R., Pieralisi, R.: Characterization of pervious concrete focusing on non-destructive testing. Rev. IBRACON Estrut. Mater. 13(3), 483–500 (2020).

[6] Nantes Hisatomi, J., Martins Filho, S.T., Tescaro Cobo, D.: Analysis of pervious concrete properties for mixtures of different W/C ratios. Rev. Gest. Soc. Ambient.18(2), 04387 (2024).

[7] Chandrappa, A.K., Biligiri, K.P.: Influence of mix parameters on pore properties and modulus of pervious concrete: an application of ultrasonic pulse velocity. Mater. Struct. 49(12), 5255–5271 (2016).

[8] Chandrappa, A.K., Biligiri, K.P.: Investigations on pervious concrete properties using ultrasonic wave applications. J. Test. Eval. 45(5), 1736–1749 (2017)

[9] Singh, R., Goel, S.: Experimental investigation on mechanical properties of binary and ternary blended pervious concrete. Front. Struct. Civ. Eng. 14 (1), 229–240 (2020).

[10] Ridengaoqier, Hatanaka, S.: Prediction of porosity of pervious concrete based on its dynamic elastic modulus. Results in Materials 10(100192), (2021).

[11] Ridengaoqier, Hatanaka, S., Palamy, P., Kurita, S.: Experimental study on the porosity evaluation of pervious concrete by using ultrasonic wave testing on surfaces. Constr. Build. Mater. 300(123959), (2021).

[12] Sathiparan, N., Jeyananthan, P., Subramaniam, D.N.: Effect of aggregate size, aggregate to cement ratio and compaction energy on ultrasonic pulse velocity of pervious concrete: prediction by an analytical model and machine learning techniques. Asian J. Civ. Eng. 25(1), 495–509 (2024)

[13] Spalvier, A., Sánchez, J., Pérez, N., 3D Modeling of Ultrasonic Wave Propagation in Pervious Concrete, under review by the Journal of Nondestructive Evaluation, (2025).

[14] Sanchez, J.A., Spalvier, A., Pérez, N.: Ultrasonic characterization of pervious concrete. In: 2023 15th IEEE International Conference on Industry Applications (INDUSCON), pp. 1284–1288. IEEE, Sao Bernardo do Campo, Brazil (2023).