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Improving the sound absorption behaviour of porous concrete using embedded resonant structures

M. Pereira, J. Carbajo, L. Godinho, J. Ramis, P. Amado-Mendes

Abstract

A relatively new concept of sound absorption herein denominated as Metaporous concrete is presented, consisting of a porous concrete-based sound absorber in which different acoustic resonators are embedded. Two finite element models were implemented, using the fluid-equivalent theory to describe Metaporous concrete solutions. A Helmholtz resonator, porous concrete samples, and a Metaporous concrete prototype were built and tested through experimental techniques based on the use of an impedance tube. The fluid-equivalent complex properties were validated with comparisons between analytical predictions and experimental data. The proposed numerical tools were presented as an efficient methodology to predict the sound absorption behavior of Metaporous concrete solutions, where an excellent approach between the simulated results and experimental data is shown. The parametric study shows efficient strategies to increase the sound absorption behavior and to feature the two sound absorption coefficient peaks provided by Metaporous concrete solutions (i.e., from the acoustic resonator and the porous concrete, respectively). The

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denominated configuration MPC₃ was highlighted because of the great proximity of these two sound absorption peaks. The inclusion of non-trivial resonant structures in porous concrete, building a Metaporous concrete, can be proposed as an excellent solution to be adopted for noise control in civil engineering exterior applications.

**Keywords:** Metaporous concrete, Sound absorption, Porous concrete

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1. Introduction

Porous absorbent materials have been widely used in passive noise control and indoor treatment. Fibers and foams are commonly used in commercial solutions because of their excellent sound absorption coefficient at high frequencies. However, for external applications, as in acoustic barriers for traffic noise mitigation, these materials require protection against environmental agents and structural reinforcement.

Because of these requirements, the interest in lightweight solutions with adequate constructive characteristics for direct application has increased over the last decades. In 2000, Krezel et al. [1] studied the application of porous concrete in noise barriers for urban freeways, while Magrini et al. [2] analyzed the acoustic absorption behavior of multilayer panels with expanded clay. The study of the acoustic properties of expanded clay with experimental characterization and theoretical representation was performed by Asdrubali et al. [3], using the model previously proposed by Horoshenkov and Swift [4] for prediction of acoustic properties of porous granular media with some
assumed pore geometry and pore size distribution close to log-normal. A systematic study of acoustic and non-acoustic properties of consolidated porous samples of expanded clay was introduced by Vašina et al. [5]. The study of consolidated lightweight and sustainable granular materials has continued in [6, 7, 8, 9]. On the other hand, Pereira et al. [10] studied the acoustic behavior of porous concrete applied in acoustic resonator solutions. Branco and Godinho [11] studied the impact sound transmission behaviour of pavement slabs mortars using expanded clay. Thermal conductivity and sound absorption behaviour of lime-cement mortars with expanded clay aggregates for coating solutions were analyzed in [12].

The investigation of the fluid-equivalent representation of porous concrete made with expanded clay has been demonstrated as relevant in the scientific community. Carbajo et al. [13] studied perforated concrete using the dual porosity theory, highlighting this solution as a friendly alternative to traditional materials because of the higher durability and the excellent strength-to-weight ratio. Pereira et al. [14] studied the influence of the water-cement ratio, the expanded clay grain size, and the sample thickness in the sound absorption behaviour, presenting the different macroscopic parameters of the Horoshenkov and Swift model obtained through an inverse technique, for each mixture analyzed. Zolanvari [15] studied the fluid-equivalent representation of porous concrete made using different aggregates.

The study of alternative strategies to increase the sound absorption
behavior of porous materials for low frequencies was proposed by Lagarrigue et al. [16], with solid inclusions embedded in a rigid frame porous material, which the authors called as metaporous material. Boutin [17] studied the propagation of the acoustic waves in a rigid porous media with inner Helmholtz resonators, while Lagarrigue et al. [18] analyzed the influence observed on the absorption coefficient and proportioned by the geometry and the arrangement of the periodic arrays of resonant inclusions embedded in a porous layer. Doutres et al. [19] demonstrated the improvements of the Helmholtz resonant inclusion in cellular porous materials through the use of transfer matrix model and experimental techniques. The coupling of acoustic resonators to increase the sound absorption behavior for low frequencies can also be observed in perforated panel solutions [20, 21, 22]. In this work, the study of the sound absorption behavior of a solution based on the inclusion of different acoustic resonators (with and without the resonator cavity filled by porous concrete) is proposed, being denominated as Metaporous concrete.

Two finite element models (2-D and 3-D) are proposed to understand the sound absorption behavior of Metaporous concrete solutions, using the fluid-equivalent theory. The porous concrete fluid-equivalent properties are defined through the Horoshenkov and Swift model, while the JCA model is used to represent the fluid-equivalent properties of the acoustic resonators. The 3-D models and the correspondent equivalent properties are validated through comparison with experimental results obtained from techniques based on the use of an impedance tube, ISO
10534-2 [23] and the two-cavities method [24], respectively. Through the 2-D finite element model, a parametric study is proposed aiming to understand the sound absorption behavior for different geometries of Metaporous concrete solutions. Different features have been analyzed, such as the influence on the sound absorption coefficient provided by resonators with and without rigid boundaries, the resonators cavity being filled or not by porous concrete, the increase of the porous concrete equivalent volume, and the presence of air cavity behind the porous concrete.

The paper's structure is as follows: Section 2 shows the theoretical background explaining how the sound absorption behavior of acoustic devices can be analyzed, and how porous concrete and acoustic resonators can be represented by the fluid-equivalent theory. Section 3 presents the methodology defined to Metaporous concrete study, showing the sample preparation, the experimental procedures, and the finite element models used. Then, Section 4 display the porous concrete macroscopic analyzes verifying the efficiency of the four parameters used in the Horoshenkov and Swift model, and the proposed finite element methodology validation. Section 4.2 presents a sound absorption parametric study of Metaporous concrete configurations, analyzing the influence of rigid resonator boundaries, the resonator cavity filled by porous concrete, and the strategy to approach the two sound absorption coefficient peaks. Finally, Section 5 summarizes the main conclusions of this work.
2. Theoretical background

2.1 Sound absorption coefficient

The sound absorption coefficient of an acoustic absorbent material, $\alpha$, can be determined by the following equation,

$$\alpha = \frac{4 \Re(Z_{s})(\rho_{0}c_{0})}{(\Re(Z_{s}\rho_{0}c_{0})+\Im(Z_{s})^2)},$$  \hspace{1cm} (1)

where, $\rho_{0}$ is the air density, $c_{0}$ is the sound propagation velocity in the air, and $Z_{s}$ is the complex surface impedance. Considering a porous material backed by a rigid wall, the $Z_{\text{spor}}$ can be determined by,

$$Z_{\text{spor}} = j\left(\frac{Z_{c}}{\phi}\right)\cot(k_{c}d_{1}),$$  \hspace{1cm} (2)

where $d_{1}$ is the material thickness, $\phi$ is the open porosity, $Z_{c}$ is its complex characteristic impedance, and $k_{c}$ is its complex wavenumber.

The analytical complex surface impedance for a classical Helmholtz acoustic resonator, $Z_{\text{res}}$, can be determined by the Equation (3), while the fluid-equivalent properties for incorporation in numerical simulations are shown in Section 2.3,

$$Z_{\text{res}} = r + j\left(\omega M - \frac{1}{\omega c_{0}}\right),$$  \hspace{1cm} (3)

where $r = \frac{\rho_{0}c_{0}k_{0}^{2}S^{2}}{2\pi}$ is the specific acoustic resistance, and $k_{0}$ is the air wave number, $\omega$ is the angular frequency, $M = \rho_{0}\frac{L'}{S}$ is the acoustic inertance, $S$ corresponds to the cross-sectional neck area, and $L'$ is the
effective neck length\(^2\). The acoustical compliance is \(C' = \frac{V}{\rho_0 c_0^2}\), and \(V\) is the volume of the resonator cavity.

It is possible to determine the surface impedance for the case of a resonator inclusion in a porous material by the following equation,

\[
\bar{Z}_s = \frac{1}{s_{\text{res}} s_{\text{por}}} \tag{4}
\]

where, \(s_2\) is the area ratio of the porous material, \(\bar{Z}_{\text{res}}\) is the complex surface impedance of the acoustic inclusion, and \(\bar{Z}_{\text{por}}\) is the complex surface impedance of a porous material. The expressions necessary to obtain the intrinsic acoustic properties of both the porous concrete and the acoustic resonator are given next.

### 2.2 Porous concrete

In the porous concrete material, granules are usually distributed differently from the fibers by following a log-normal pore distribution, resulting in smaller porosity and higher tortuosity. The absorption coefficient of these materials depends on the size of the pores, the porosity, the tortuosity, and the thickness of the material sample.

In this work, the semi phenomenological model proposed by Horoshenkov and Swift [4] is used to predict and represent the acoustic behavior for the porous concrete. This model considers four

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\(^2\) \(L' = L + 1.7r_n\) for outer and flanged, and \(L' = L + 1.5r_n\) for outer and unflaged. \(L\) is the neck length and \(r_n\) is the neck radius.
macroscopic parameters, to list: air-flow resistivity, $\sigma$, open porosity, $\phi$, tortuosity, $\alpha_\infty$, and standard deviation of the pore size, $\sigma_p$. It has been derived assuming rigid frame granular media with a log-normal pore size distribution. To derive the characteristic impedance, $\tilde{Z}_c$, and the wavenumber, $\tilde{k}_c$, of the material:

$$\tilde{Z}_c = \sqrt{\tilde{\rho}_{eq}\tilde{K}_{eq}},$$  
$$\tilde{k}_c = \frac{\omega}{\sqrt{\tilde{\rho}_{eq}/\tilde{K}_{eq}}},$$

where $\tilde{\rho}_{eq}$ is the complex density, and $\tilde{K}_{eq}$ is the bulk modulus. These intrinsic properties of the material can be calculated using the following equations:

$$\tilde{\rho}_{eq}(\omega) = \frac{\alpha_\infty}{\phi}(\rho_0 - j\frac{\sigma_\phi}{\omega_\alpha_\infty}\tilde{F}(\omega)),$$
$$\tilde{K}_{eq}(\omega) = \frac{\gamma P_0}{\phi} \left( \gamma - \frac{\rho_0(\gamma-1)}{\rho_0-j\omega\alpha_\infty\nuP(\omega\Np)} \right)^{-1},$$

The term $\gamma$ is the ratio of specific heats, $P_0$ is the atmospheric pressure, and $\Np$ is the Prandtl number, and $\tilde{F}(\omega)$ is the viscosity correction function, which can be presented in the form of a Padé approximation as:

$$\tilde{F}(\omega) \approx \frac{1+a_1\varepsilon+a_2\varepsilon^2}{1+b_1\varepsilon}.$$  

Here, the term $\varepsilon = \sqrt{j\omega\rho_0\alpha_\infty/\sigma_\phi}$ is a dimensionless parameter, $a_1 = \frac{\theta_1}{\theta_2}$, $a_2 = \theta_1$, $b_1 = a_1$. The terms $\theta_1$ e $\theta_2$ are pore shape factors defined by the porous geometry. When a circular pore shape is
assumed, $\xi = [\sigma_p \ln(2)]^2$, obtaining the two asymptotic expansion coefficients,

$$\theta_1 = \left(\frac{4}{5}\right) e^{4\xi} - 1, \quad (10)$$

$$\theta_2 = \left(\frac{1}{\sqrt{2}}\right) e^{3\xi/2}, \quad (11)$$

2.3 Acoustic resonators

When the air mass in the neck is excited by a sound wave a vibration occurs at a particular frequency, resulting in a specific response of the sound wave. The resonant frequency of these devices can be tuned through geometric dimensions changes [25, 26, 27, 28, 29]. When combined with porous materials, acoustic resonators can provide an increase in the sound absorption coefficient in specific frequencies [16, 17, 18, 19]. Two different types of resonant structures are herein analyzed namely, the classical Helmholtz resonator and the slit-like resonator.

To represent these resonant structures as a fluid-equivalent, the neck properties were determined through the JCA model [30]. This model considers five macroscopic parameters, being the airflow resistivity, $\sigma$, the open porosity, $\phi$, the tortuosity, $\alpha_\infty$, the viscous characteristic length, $\Lambda$, and the thermal characteristic length, $\Lambda'$. Where the complex
density, $\bar{\rho}_{eq}$, and the bulk modulus, $\bar{K}_{eq}(\omega)$, can be determined, respectively, by the following equations,

$$\bar{\rho}_{eq}(\omega) = \frac{\rho_0 \sigma \omega}{\phi} \left[ 1 + \frac{\sigma \phi}{1+\rho_0} \left( \frac{4\rho_0 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2} \right)^{1/2} \right], \quad (12)$$

$$\bar{K}_{eq}(\omega) = \frac{\gamma \rho_0/\phi}{\left[ \gamma^{-1} \frac{1+\sigma \phi}{1+\rho_0} \left( \frac{4\rho_0 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2} \right)^{1/2} \right]}, \quad (13)$$

$\eta$ is the air viscosity.

Table 1 summarizes the macroscopic parameters for a neck, with either a circular or a slit geometry [31].

<table>
<thead>
<tr>
<th>Cross-sectional Shape</th>
<th>Airflow resistivity $\sigma$ [Ns/m$^4$]</th>
<th>Tortuosity $\alpha_o$ [-]</th>
<th>Viscous characteristic length $\Lambda$ [m]</th>
<th>Thermal characteristic length $\Lambda'$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>$\frac{8\eta}{\phi_c R_h^2}$</td>
<td>$1 + \left( \frac{2 \varepsilon_c}{l_c} \right) R_h$</td>
<td>$\bar{R}_h$</td>
<td>$\bar{R}_h$</td>
</tr>
<tr>
<td>Slit</td>
<td>$\frac{12\eta}{\phi_s R_h^2}$</td>
<td>$1 + \left( \frac{2 \varepsilon_s}{l_s} \right) \left( \frac{1}{0.81} \right) \left( \frac{8\eta}{\phi_s \sigma} \right)^{1/2} R_h$</td>
<td>$\bar{R}_h$</td>
<td>$\bar{R}_h$</td>
</tr>
</tbody>
</table>

The terms $\phi_c$ and $\phi_s$ correspond to the open porosity of the circular and slit cross-sections, respectively; $\varepsilon_c = 0.48\sqrt{\pi R_h^2}(1 - 1.14 \sqrt{\phi_c})$ and $\varepsilon_s = \phi_s$ are, respectively, the correction length for circular and slit cross-section [32]; $l_c$ is the circular neck length, and $l_s$ is the slit neck.
length. The hydraulic radius $R_h$ for each of these cross-sectional shapes is shown in Figure 1.

![Figure 1: Schematic representation, in plane view, of the hydraulic radius for the two different cross-sectional shapes.](image)

3. Methodology

The present section describes the proposed methodology to study the sound absorption behavior of porous concrete using embedded resonant structures, presenting the specimens preparation process, the acoustic characterization, the strategy to the macroscopic parameters evaluation, and the numerical model used to predict the metaporous concrete sound absorption coefficient. Figure 2 presents a schematic diagram with the methodology adopted for the parametric study to be presented in Section 4.
3.1 Samples preparation

The porous concrete samples were produced using expanded clay aggregates with grain size of 0-2 mm. Twelve samples of two different mixtures were prepared (six for each mixture), and called M₂ and M₃, maintaining the nomenclature presented in previous work [14]. The corresponding sound absorption curves can be observed in Figure 6 of the same previous work. The proportions between material components, in weight (kg), are presented in Table 2, where all samples have 10.1 cm of diameter, and thickness of 4, 6 and 8 cm. The specimens were extracted from the moulds to complete the cure in open air for 30 days.

<table>
<thead>
<tr>
<th>Granular mixture</th>
<th>Aggregate (%)</th>
<th>Cement (%)</th>
<th>Water (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture 2</td>
<td>43.96</td>
<td>37.36</td>
<td>18.68</td>
</tr>
<tr>
<td>Mixture 3</td>
<td>40.17</td>
<td>38.89</td>
<td>19.92</td>
</tr>
</tbody>
</table>

Table 2. Materials proportions in weight (kg) of the produced samples
The resonator prototype has a cylindrical cavity printed in Polylactic Acid material (PLA) using a Blocks One 3-D printer, with the printing infill being set to 100%. The cylindrical cavity had an internal cross-section of 5.95 cm of diameter, $d_{cav}$, and 2.95 cm of length, $l_{cav}$. A stainless steel cylindrical neck of circular cross-section with 1 cm of diameter, $d_c$, and 6 cm of length, $l_c$, was coupled to the PLA cavity leading to an impervious cylindrical Helmholtz resonator.

The Helmholtz resonator was embedded in a porous concrete sample with 4 cm of thickness and mixture $M_3$, making a Metaporous concrete prototype for testing. Figure 3 illustrates the proposed prototype, Figure 3a schematizes the resonator proposed and its dimensions, and Figure 3b presents two different views of the prototype tested.

![Figure 3: Metaporous concrete prototype: (a) Dimensions of the designed Helmholtz resonator; (b) Picture of the resonator embedded in porous concrete resulting in a Metaporous concrete sample.](image)
3.2 Acoustic characterization

In this work, an experimental procedure based on the use of an impedance tube was used to characterize the normal incidence acoustic properties of the Metaporous concrete samples. As described in ISO 10534-2 [23], these properties can be obtained from the transfer function between two microphones. To obtain the intrinsic acoustic properties of the porous concrete samples, the Two-Cavity Method proposed by Utsuno et al. [24] was used.

The impedance tube used in the present work has a circular cross-section of 10.1 cm diameter, the cut-off frequency being approximately 1600 Hz for the chosen microphone spacing. A white noise signal was used to excite the speaker from the analyzer OR34 Compact Analyzer, the sound pressure was measured using two microphones B&K Type 4188 1/2, positioned at 16 cm and 10 cm from the sample surface, and the pressure data post-processed in Matlab, to obtain both the surface impedance and the sound absorption coefficients. A schematic representation of the two experimental setups is presented in Figure 4, where the term \( d_1 \) is the sample thickness, and \( D \) is the air cavity thickness.

![Schematic diagram](a)
Figure 4: Schematic representation of the impedance tube experimental setup: (a) Represents the setup with rigid termination in the sample back. (b) Shows the setup with an air cavity, $D$, between the sample and the rigid termination.

The two-cavity method is based on two measurements of the same sample through the ISO 10534-2 procedure. Each measurement uses a different air cavity depth, $D$, between the sample and the rigid termination. The complex characteristic impedance, $\tilde{Z}_c$, and the complex wavenumber, $\tilde{k}_c$, can be determined, respectively, by the following equations,

$$\tilde{Z}_c = \sqrt{\frac{\tilde{Z}_{s1}\tilde{Z}_{s2}(Z_1-Z'_1)-Z_1Z'_1(\tilde{Z}_{s1}\tilde{Z}_{s2})}{(Z_1-Z'_1)-(\tilde{Z}_{s1}\tilde{Z}_{s2})}}, \quad (14)$$

$$\tilde{k}_c = \frac{j}{2d_1}\ln\left(\frac{\tilde{Z}_{s1}+\tilde{Z}_c\tilde{Z}_{s2}}{\tilde{Z}_{s1}-\tilde{Z}_c}\right). \quad (15)$$

where $d_1$ is the sample thickness, $\tilde{Z}_{s1}$ is the complex surface impedance measured with the first air cavity depth $D$, $\tilde{Z}_{s2}$ is the complex surface impedance measured with the second air cavity depth $D'$. $Z_1$ and $Z'_1$ denote the acoustic impedance of each air cavity,

$$Z_1 = -j\rho_0 c_0 \cot(k_0 D), \quad (16)$$
In this study, the measurements were performed for a rigid termination and an air cavity depth \( D = 2 \) cm. This option preserves the method's validity and allows minimizing the number of measurements for each sample to determine both its sound absorption coefficient and its intrinsic acoustic properties.

### 3.3 Determination of the macroscopic parameters

The four macroscopic parameters required to represent the porous concrete as fluid-equivalent through the Horoshenkov and Swift model were previously obtained in [14]. The inverse technique was performed using a genetic algorithm in which the objective function was based on the quadratic sum of errors between the analytical and experimental data, along a frequency range with \( n_f \) discrete frequency values,

\[
\text{OF}(\omega) = \sum_{i=1}^{n_f} |\alpha_{\text{ana}} - \alpha_{\text{exp}}|, \tag{18}
\]

where \( \alpha_{\text{ana}} \) is the absorption coefficient obtained from the Horoshenkov and Swift model, and \( \alpha_{\text{exp}} \) is the experimental absorption coefficient. The open porosity was the only macroscopic parameter experimentally determined, using the water saturation method.

Table 3 introduces the macroscopic parameters' values for the two different mixtures, \( M_2 \) and \( M_3 \), previously presented in Section 3.1.
Table 3: Macroscopic parameters previously obtained in [14].

<table>
<thead>
<tr>
<th>Aggregates of 0-2 mm</th>
<th>Airflow Resistivity $\sigma$ [Ns/m$^4$]</th>
<th>Open porosity $\phi$ [-]</th>
<th>Tortuosity $\alpha_\infty$ [-]</th>
<th>The standard deviation of the pore size $\sigma_p$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixture 2</td>
<td>3896.06</td>
<td>0.46</td>
<td>1.89</td>
<td>0.25</td>
</tr>
<tr>
<td>Mixture 3</td>
<td>7171.53</td>
<td>0.36</td>
<td>2.73</td>
<td>0.41</td>
</tr>
</tbody>
</table>

The two-cavity method described in Section 3.2 was adopted to verify the complex properties, $\tilde{Z}_c$ and $\tilde{k}_c$, obtained through the Horoshenkov and Swift model using the presented macroscopic parameters. Figure 5 compares these complex properties of the porous concrete $M_7$ with 4cm of thickness, with Figure 5a displaying the $\tilde{Z}_c$ comparison, and Figure 5b exhibiting the $\tilde{k}_c$. An excellent agreement can be observed between the analytical prediction and the experimental data.

*Figure 5: Complex properties comparison between the Horoshenkov and Swift representation and the two-cavity experimental data: (a) Characteristic impedance, $\tilde{Z}_c$; (b) Complex wavenumber, $\tilde{k}_c$.*

Through the complex properties analyzed, the use of these macroscopic parameters was validated, making possible to represent and predict the
porous concrete for different samples’ thicknesses and geometries. This new study is represented in Figure 6, where Figure 6a corresponds to the sound absorption prediction of $M_2$ for different sample thicknesses, up to 25 cm. The lighter color corresponds to the frequency range with higher values of the absorption coefficient. In contrast, the darker colors represent the predicted lower values of the sound absorption coefficient.

![Image of Figure 6a and 6b](image)

*Figure 6: Porous concrete $M_2$ acoustic behavior prediction: (a) Sound absorption coefficient analyzes for different sample thicknesses; (b) Sound absorption coefficient in comparison between predicted and experimental characteristics for samples with 6 cm of thickness.*

The specific case of mixture for $M_2$ and sample thickness of 6 cm is highlighted by the red dashed line in Figure 6a., corresponding to an interesting mid-frequency sound absorption behavior. Figure 6b illustrates the comparison between the predicted sound absorption and the experimental result for the same displayed thickness, exhibiting an almost perfect match for frequencies above 500 Hz. It becomes therefore possible to use the equivalent-fluid representation in the subsequent finite element simulations.
3.4 Numerical modelling

The Finite Element Method (FEM) was implemented in Matlab to solve the partial differential equations that govern the propagation of sound waves in fluid media. In the acoustic study, the objective of the numerical simulation is to discretize the domain into sufficiently small elements and calculate the particle velocities and acoustic pressures on the mesh nodes, which represent the fluid inside the tubes.

The linear wave equation governs the propagation of small amplitudes sound waves in a homogeneous media as that involved in the interior acoustic problem under study. Properties that describe the fluid domain can be applied, as well as the boundary conditions established in the problem [33, 34]. The acoustic field in the frequency domain is thus calculated through the Helmholtz equation, which allows accounting for the effects of finite geometry of the Metaporous concrete. This set of equations can be presented in matrix form as,

\[ \frac{1}{2} \mathbf{Q} \frac{d^2 \mathbf{p}(t)}{dt^2} + \mathbf{D} \frac{d \mathbf{p}(t)}{dt} + \mathbf{H} \mathbf{p}(t) = \mathbf{q}(t), \]

where \( \mathbf{Q} \) is the global inertia matrix, \( \mathbf{D} \) is the global dissipation matrix, and \( \mathbf{H} \) is the global stiffness matrix. The terms \( \mathbf{q} \) and \( \mathbf{p} \) correspond to the nodal excitation vector and the acoustic pressure vector, respectively. The acoustic pressure distribution is obtained solving the partial differential equation system for each temporal instant, \( t \), seeing the connectivity between each element. Considering a harmonic
solution, $p(t) = A e^{i\omega t}$, with amplitude $A$, the matrix equation can be solved using the direct method in the frequency domain as,

$$[H + j\omega D - \omega^2 Q]p = q.$$  \hspace{1cm} (20)  

Figure 7 schematically represents the two finite element models proposed to study the acoustic behavior of the Metaporous concrete: a 2-D model and a 3-D model. The 2-D model was used to study the solution with a slit-like neck resonator, while the 3-D model was performed to analyze circular neck geometries.

![Diagram](a)\hspace{1cm}![Diagram](b)

*Figure 7: Schematic representation of the two proposed FEM models: (a) 2-D FEM; (b) 3-D FEM.*
Both proposed models are based on impedance tube representation, where the sound absorption coefficient was determined for a unit cell (i.e., porous concrete by a single neck), by reproducing the ISO 10534-2 procedure in the numerical model. Therefore, the Horoshenkov and Swift model was used to describe the porous concrete regions of the unit cell, while the JCA model was used for the properties of the neck. The fluid inside the impedance tube and the cavities were defined as air. A harmonic sound pressure wave excitation was defined on the left side of the tube. The acoustic pressure points are positioned in 16 and 10 cm from the sample surface, reproducing the microphone positions in the experimental setup. The frequency range of analysis was performed from 10 Hz, in 10 Hz steps, up to the frequencies of 1600 Hz, for the 3-D case, and 2000 Hz for the 2-D case. The finite element mesh used triangular elements, with a maximum size of 0.0089 m, with a discretization criteria of 20 elements per wavelength.

4. Results

4.1 Numerical model validation

This section aims to validate the proposed model, by developing a numerical tool for Metaporous concrete studies through the fluid-equivalent theory and the finite element method.

The impedance tube method was used to analyze the sound absorption coefficient of each acoustic device. The experimental characterization method was previously defined in Section 3.2. Three experimental tests
were performed: the Helmholtz prototype with the neck coupled in a rigid termination, with the opened area of $S$; a porous concrete sample $M_3$ with 4 cm thickness; the Metaporous concrete prototype previously displayed in Section 3.1.

The model 3-D FEM was used to simulate the Helmholtz resonator and the Metaporous concrete prototype, following the methodology based on the fluid-equivalent theory defined in Section 3. Figure 8 represents the comparison between the experimental data and the numerically simulated results, in terms of the sound absorption coefficient of the proposed configurations.

![Figure 8: Comparison between the sound absorption coefficient numerically simulated and the measured Helmholtz resonator, the porous concrete $M_3$ with 4 cm thickness, and the Metaporous concrete prototype.](image)

The proposed numerical methodology displayed exhibits close agreement between the Helmholtz resonator results and the Metaporous
concrete prototype experimentally tested. This numerical model considering the fluid-equivalent theory can be highlighted as an excellent tool to predict the acoustic behavior of Metaporous concrete solutions, allowing to perform the parametric study in the next Section.

4.2 Parametric study

The present section aims to study some strategies to increase the sound absorption coefficient and provides the approximation of the two observed sound absorption peaks. For this purpose, the effect of the resonator with non-rigid boundaries is studied in Section 4.2.1, then the influence of resonator cavities filled by porous concrete is analysed in Section 4.2.2, and also the addition of new cavities behind the porous concrete is proposed and performed in Section 4.2.3.

4.2.1 Influence of using non-rigid boundaries in the resonator

As it was observed in [10], the resonators built with porous concrete without rigid boundaries present a single peak of sound absorption coefficient that cannot be predicted by analytical equations describing Helmholtz resonators. However, it is important to understand in more detail the behavior of such structures, which do not have rigid boundaries separating the resonator from the porous concrete. Numerical simulations were thus performed using the 2-D finite element model previously presented in Section 3.4 to highlight and better understand the influence of the boundary conditions. The porous concrete was represented using the Horoshenkov and Swift model and
the macroscopic parameters of $M_2$, which were formerly presented in Table 3.

The geometric dimensions of the proposed Metaporous concrete configurations are presented in Table 4. Figure 9 schematically shows these geometries, being denominated as MPC and $\text{MPC}_2$, where the $\text{MPC}_2$ corresponds to resonator cavity with diameter $d_{cav_2}$. The red dashed lines in Figure 9a represent the resonator boundaries.

![Figure 9: Metaporous concrete resonators with and without rigid boundaries: (a) Schematic representation of the geometries MPC and $\text{MPC}_2$; (b) Predicted sound absorption coefficient of the proposed geometries.](image)

**Table 4: Geometry dimensions of the proposed Metaporous concrete configurations.**

<table>
<thead>
<tr>
<th>Geometry dimensions</th>
<th>Thickness / Length [cm]</th>
<th>Diameter [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slit neck</td>
<td>$l_{slit} = 3$</td>
<td>$d_{slit} = 0.25$</td>
</tr>
<tr>
<td>Resonator cavity 1</td>
<td>$l_{cav_1} = 3$</td>
<td>$d_{cav_1} = 3$</td>
</tr>
<tr>
<td>Resonator cavity 2</td>
<td>$l_{cav_2} = 3$</td>
<td>$d_{cav_2} = 6$</td>
</tr>
<tr>
<td>Porous concrete / waveguide</td>
<td>$h_{por} = 3$</td>
<td>$d_{total} = 6$</td>
</tr>
</tbody>
</table>
Figure 9b illustrates the simulated absorption coefficients for the proposed configurations of Metaporous concrete. In the case without rigid resonator boundaries, the sample with the largest air cavity, $MPC_2$, achieves greater sound absorption at lower frequencies, its sound absorption peak being at approximately 820 Hz. In comparison, the geometry $MPC$ shows a peak at approximately 1020 Hz.

For the configurations considering rigid resonator boundaries, geometries $MPC$ and $MPC_2$, two different peaks can be noted in the sound absorption coefficient. One corresponds to the acoustic resonator and the other to the porous concrete sound absorbing behavior. The geometry $MPC_2$ shows a peak at 340 Hz. In contrast, the maximum sound absorption geometry $MPC$ occurs at a frequency of 490 Hz, where the configuration with the deepest backing cavity results in an improved sound absorption at low frequencies. These two geometries have the same porous concrete thickness in the sound absorption observed in 2000 Hz for both cases.

To better illustrate the contribution of each part of the Metaporous concrete in the sound absorption, Figure 9 represents the sound pressure maps of $MPC$, with and without rigid resonator boundaries, for frequencies corresponding to the peaks observed in Figure 9b.
Figure 10: Sound pressure maps corresponding to the frequency of sound absorption peak of MPC, previously displayed: (a) at 1020 Hz, without rigid resonator boundaries; (b) at 490 Hz; (c) at 2000 Hz.

Figure 10a displays the sound pressure maps for the geometry MPC without rigid resonator boundaries, at a frequency of 1020 Hz, where the effect provided by an air cavity in the porous concrete back can be observed, resulting in a shift to low frequencies of the only sound absorption coefficient peak. Figure 10b presents the sound pressure map at a frequency of 490 Hz and the geometry MPC. With the resonator providing the greater influence in the sound absorption, and the highest sound pressure values being observed inside the resonator cavity. Finally, in Figure 10c, the frequency analyzed is 2000 Hz, and the most contribution of the porous concrete in the sound absorption phenomena can be noted, as the highest values are in the porous concrete geometry, while the resonator presents lower values. Therefore, through this analysis, it was possible to highlight the necessity of rigid resonator boundaries to properly achieve the additional resonance effect. Therefore, in the next section, the influence of filling the acoustic resonator cavity by porous concrete will be analyzed.
4.2.2 Influence of filling the resonator cavity with porous concrete

In this section, the assessment of further increasing the sound absorption performance of the Metaporous concrete is studied by filling the resonator cavity with porous concrete. Figure 11 presents the geometries studied in this section, where Figure 11a shows the same geometric dimensions previously defined as MPC and MPC$_2$. However, in this case, the porous concrete is also filling the resonator cavity, being now nominated as MPC$_b$ and MPC$_{2b}$, with the same dimensions of MPC and MPC$_2$, respectively. A comparison of the sound absorption coefficient curves, for all the configurations presented so far, is depicted in Figure 11b.

![Figure 11: Metaporous concrete geometries with resonator cavities filled by porous concrete: (a) Geometries MPC$_b$ and MPC$_{2b}$; (b) Influence of the resonator cavity filled by porous concrete in the sound absorption coefficient.](image)

It can be observed, in Figure 11b, that the sound absorption coefficient peak contribution from the porous concrete appears in the same frequency of 2000 Hz, while the sound absorption coefficient peak from the acoustic resonator is shifted to higher frequencies. This occurs
because of the sound energy dissipation inside the resonator cavity between the solid and fluid phases (interstitial to the pores) from the porous concrete. The sound absorption coefficient peak of 490 Hz from MPC is shifted to 610 Hz in MPC_b, and an increase of approximately 0.20 can be observed. A similar effect occurs between MPC_2 and MPC_{2b}, where the sound absorption coefficient peak is moved from 340 Hz to 430 Hz, and an increase of approximately 0.30 is highlighted.

4.2.3 Influence of adding an air cavity behind the porous concrete

Looking to provide an approximation between the two sound absorption coefficient peaks exhibited by the Metaporous concrete solutions, the presence of porous concrete inside the resonator cavity was highlighted. In the previous cases, a strategy was shown to shift the sound absorption coefficient peaks provided by the acoustic resonator. In this section, additional strategies were formulated, intending to move the peak corresponding to the porous concrete sound absorption to lower frequencies, making it closer to that of the resonator, thus widening the whole effective absorption bandwidth.

Figure 12 illustrates another four geometries studied, named as MPC_c, MPC_d, MPC_e, and MPC_f, where the acoustic resonator has the same dimensions as of the MPC and MPC_b models. As can be seen, two new cavities were added in the back of the porous concrete.
Figure 12: Metaporous concrete with new cavities added in the back of the MPC and MPC₂, respectively. These cavities are considered as air in MPC₁ and MPC₃, and filled by porous concrete in MPC₄ and MPC₅.

Figure 13 presents the sound absorption coefficients calculated for these four configurations. It is observed that the addition of an air cavity or the increase of the porous concrete volume, provides the expected shift in the second sound absorption coefficient peak to lower frequencies. The configurations presenting an increased quantity of porous concrete, MPC₄ and MPC₅, demonstrate a displacement of the second absorption peak to approximately 1100 Hz, in addition to an increase of approximately 0.12 in the sound absorption coefficient. The configurations with the air cavity addition, MPC₁ and MPC₃, showed the second peak around 930 Hz without an increment in the sound absorption coefficient.
For these analyzed Metaporous concrete geometries, the MPCd must be highlighted. This configuration, with an air cavity in the back of the porous concrete and with the acoustic resonator cavity filled by porous concrete, provides a close proximity of the two sound absorption peaks, widening the frequency range of the sound absorption coefficient.

The presented results have shown that the strategy of coupling porous concrete and acoustic resonators for sound absorption external application can be very efficient. The proposed methodology with the use of the fluid-equivalent theory in finite element models also demonstrated to be an excellent tool for Metaporous concrete geometry optimization and acoustic solution predictions.
5. Conclusions

This work proposes a relatively new concept herein denominated as Metaporous concrete, which consists of a porous concrete-based sound absorber in which different acoustic resonator solutions are embedded.

The fluid-equivalent theory, through analytical models based on macroscopic parameters, was used to represent each part that composes a Metaporous concrete. Two different numerical models were implemented using the finite element methodology to predict and describe the sound absorption coefficient of various geometries. Experimental techniques based on the use of an impedance tube were performed to validate these proposed methodologies, verifying the porous concrete complex properties and the sound absorption coefficient of the Helmholtz resonator and the Metaporous concrete prototype.

A parametric study was performed, showing the importance of the acoustic resonator with rigid boundaries to provide a new sound absorption coefficient peak in a specific frequency range determined through the acoustic resonator dimensions. The effect of the acoustic resonator cavity being filled by porous concrete has shown an interesting increase and a frequency shift in the corresponding sound absorption peak to higher frequencies. The cavity added in the back of the porous concrete, filled by air or by porous concrete, provides a displacement of the porous concrete contribution in the sound absorption coefficient to lower frequencies. The configuration called
MPC\_d can be highlighted because of the interesting proximity between the two absorption peaks that describe the sound absorption coefficient of Metaporeous concrete solutions.

In summary, the inclusion of non-trivial resonant structures in the porous concrete was shown to significantly enhance the sound absorption performance of such devices, thus becoming an excellent solution to be adopted for noise control in civil engineering exterior applications.

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HIGHLIGHTS

- Analysis of a porous concrete-based sound absorber in which different acoustic resonators are embedded.
- Fluid-equivalent theory and two finite element models were used to describe sound absorption behavior of metaporous concrete solutions.
- The increase of sound absorption behavior while featuring the sound absorption coefficient peaks of metaporous concrete analyzed in parametric study.
- The inclusion of non-trivial resonant structures in porous concrete proposed for noise control in civil engineering exterior applications.
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: