

Article

Granular Pumice Stone: A Natural Double-Porosity Sound-Absorbing Material

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Abstract: Pumice forms when a volcanic explosion ejects highly pressurized, superheated rock, rapidly cooling and depressurizing, resulting in a porous structure. In countries with high volcanic activity, pumice stone is a low-cost natural material that is lightweight, non-toxic, eco-friendly, durable, and heat-resistant. Among other applications, pumice has been used as an aggregate to produce lightweight concrete or cementitious material to produce blended cement or geopolymer. Since pumice stone is highly porous, it could be used as a naturally occurring multiscale porous sound-absorbing material, which may add interesting properties for absorbing sound energy. Normally, a double-porosity granular material presents higher sound absorption at low frequencies than a solid-grain material with the same mesoscopic characteristics at a reduced weight. This study uses theoretical and experimental approaches to investigate the sound absorption characteristics of granular pumice samples. The tests were conducted on crushed pumice stones in granular form. The study suggests that pumice stones can be used as a novel material for sound absorption in room acoustics and noise control applications.

Keywords: acoustic materials; pumice stone; natural materials; sound absorption; double-porosity; noise control



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1. Introduction

Sound-absorbing materials are essential to modern buildings where foams, fiberglass, and rock wool have been widely used to improve acoustic comfort, despite their high carbon footprint.

Due to the growing concern about the harmful effects of waste pollution and energy consumption in the manufacture of building materials, there is an increasing trend to use building products of natural origin and with a low carbon footprint. In this regard, numerous studies have been presented on using natural fibers, waste, and recyclable alternatives to traditional materials to achieve the goals of sustainable construction [1,2]. These studies have been particularly intense in developing sustainable and environmentally friendly concrete [3]. One such natural material is pumice, whose name derives from the Latin word *pumex* which relates to “spuma”, i.e., foam [4]. Pumice is naturally produced when a volcanic eruption violently ejects an extremely heated and highly pressurized rock. The depressurization causes the gases dissolved in the lava to become less soluble, thus forming bubbles. The combination of fast cooling and depressurization traps these bubbles in a solid matrix, resulting in a highly porous structure. This material is formed mainly

of silica (SiO_2) and alumina (Al_2O_3), which comprise approximately 60% and 16% of its composition, respectively [5].

In countries with high volcanic activity, pumice stone is a low-cost natural raw material with several valuable qualities. It is lightweight, non-toxic, eco-friendly, durable, and heat-resistant. Among other applications, such as smoothing and polishing powder, or water and wastewater treatment [6], pumice has been used as an aggregate to produce lightweight concrete or cementitious material to produce blended cement or geopolymer. Rashad [7] reviewed the benefits, shortages, and applications of concrete and mortar based on conventional cement when pumice is incorporated as a coarse or fine lightweight aggregate substitution. The characteristics studied were thermal conductivity, permeability, water absorption, fire and chemical resistance, and mechanical strength. A comprehensive review of pumice's physical, chemical, and morphological characteristics as a concrete aggregate has recently been presented [4].

Since pumice stone is highly porous, it could potentially be used as a sound-absorbing material. The pumice has a porous structure constituted by tiny air voids or bubbles formed when molten lava gas is rapidly cooled. The air voids are interconnected and sometimes elongated [4,7]. Thus, in a granular form, pumice could be regarded as a naturally occurring multiscale porous material [8], which may add interesting properties for absorbing sound energy. Other authors have presented examples of naturally occurring double-porosity materials for sound absorption [9,10]. Normally, a double-porosity granular material presents higher sound absorption at low frequencies than a solid-grain material with the same mesoscopic characteristics at a reduced weight [11].

Although the use of pumice as a lightweight aggregate has been widely documented in the technical literature, information on its use as a sound-absorbing material is limited [12–14]. Only a few studies have dealt with fly ash-based geopolymer concrete with different aggregates [15]. The shock-absorbing capability of lightweight concrete utilizing volcanic pumice as coarse aggregate was experimentally investigated by Onoue et al. [16]. They showed that lightweight concrete has a superior shock-absorbing capacity compared to traditional concrete with crushed limestone as coarse aggregate. Sariisik and Sariisik [17] tested the sound insulation of blocks composed of expanded polystyrene foam and lightweight concrete containing pumice aggregate. They reported insulation values of up to 60 dB for a wall of 20 cm thick blocks with a 562 kg/m^3 density.

Canbolat et al. [18] studied multilayer acoustic and thermal insulation surfaces. They added pumice stone powder in three different concentrations and two different sizes to textile materials coated with adhesive to improve adherence to a wall. Their experimental results demonstrated that multilayer surfaces' acoustic and thermal properties increase with the increasing concentration of pumice stone powder and the decreasing sizes of pumice stone particles. In addition, increasing the concentration and particle size of pumice stone powder decreases the air permeability of multilayer surfaces.

Bozkurt et al. [19] investigated the effect of using pumice as a light aggregate instead of river sand in the mortar mixture to increase sound absorption in a plaster layer. Their experimental results reported an increased sound absorption coefficient in the 1400–2700 Hz range when using pumice aggregates of 2–4 mm. Additionally, they showed that as the pumice aggregate volumetric ratio increases, the open porosity and capillary water absorption ratios also increase. However, the authors did not provide any explanations for the improved sound absorption's physical origin. Similar experimental results were presented by Soyaslan [20] in a composite where pumice with a grain size between 2.38 and 4.76 mm was mixed with different percentages of polyurethane.

More recently, Kapicová et al. [21] developed sound-absorbing pervious concrete for manufacturing interior cladding panels. They tested different aggregate sizes and

their combinations, concluding that the best acoustic results were obtained for samples containing 3–7 mm pumice aggregate when measured in an impedance tube. Without determining the sound absorption mechanisms involved, the importance of using different void types for acoustic absorption was observed, i.e., voids created between the aggregate and voids within the aggregate itself. More practically, Giraldo and Colorado [22] evaluated the acoustic performance of different sound-absorbing materials and balcony configurations used in the facades of urban street canyons. They reported environmental noise mitigation of about 5 dB at high frequencies by placing materials such as pumice stone and refractory brick on the facade surfaces.

In summary, most research on pumice stone aggregate has aimed to report the mechanical properties of composites, and a few have reported sound absorption results. The lack of literature regarding the sound absorption characteristics of granular pumice stone is the research gap this work fills in. The specific objective of this study is to explain the sound absorption properties of granular pumice stones, a naturally occurring multiscale material, by applying the established theory of acoustics of double-porosity materials to describe their sound absorption behavior.

We emphasize that the theory of acoustic wave propagation in a granular material having no internal pores in the grains [23] does not accurately predict the sound-absorbing behavior of granular pumice [24]. Hence, this work advances the current knowledge in sound absorption of naturally occurring materials by using theoretical and experimental approaches to prove that the sound absorption characteristics of granular pumice stones can be accurately predicted when their multiscale microstructure is properly considered.

2. Materials and Methods

2.1. Theoretical Approach

Two distinct local characteristic lengths can be identified in double-porosity granular materials [11]. These determine the existing air-saturated pore networks and are associated to the size of the voids formed in between the grains, namely ℓ_p , and that of small pores in the grains ℓ_m . Depending on the ratio between these two local characteristic sizes, i.e., $\epsilon = \ell_m / \ell_p$, different macroscopic long-wavelength acoustic behavior arises. For a moderate ratio, that is, $\epsilon = O(10^{-1})$, which is a case known as low permeability contrast [8], a single constant pressure field exists at the local scale and the effective parameters of the granular medium, namely the effective dynamic viscous permeability $\mathcal{K}(\omega)$ and compressibility $\mathcal{C}(\omega)$, are determined, in a first approximation, by weighted arithmetic means, respectively, involving the viscous permeabilities and compressibilities of the inter-granular voids and small pores in the grains. On the other hand, a high contrast of permeabilities, observed when, e.g., $\epsilon = O(10^{-3})$, leads to the co-existence of local pressure fields. Specifically, the sound pressure in the inter-granular voids is constant, while that inside the grains varies locally. Such a pressure imbalance, which has its physical origin in visco-thermal phenomena, leads to additional sound energy dissipation via pressure diffusion [8,11].

Simple expressions that allow capturing the two mentioned cases, that is, low and high permeability contrast in double-porosity granular materials, are as follows:

$$\mathcal{K}(\omega) = \mathcal{K}_p(\omega) + (1 - \phi_p)\mathcal{K}_m(\omega), \quad (1)$$

$$\mathcal{C}(\omega) = \mathcal{C}_p(\omega) + (1 - \phi_p)\mathcal{C}_m(\omega)\mathcal{F}(\omega), \quad (2)$$

where ω is the angular frequency, $\mathcal{K}_p$ and $\mathcal{C}_p$ are the dynamic viscous permeability and compressibility of the fluid equivalent to the air saturating the inter-granular voids, and $\mathcal{K}_m$ and $\mathcal{C}_m$ are the analogues of the micropores in the grains. The porosity associated to the inter-granular voids is denoted as ϕ_p , while $\mathcal{F}$ corresponds to the ratio between the spatially

averaged pressure in the grains to that in the inter-granular voids. It is worth noting that Equation (1) reduces to $\mathcal{K} \approx \mathcal{K}_p$ for materials with highly contrasted permeabilities. On the other hand, setting $\mathcal{F} = 1$ in Equation (2) provides the effective compressibility of a double-porosity material with low permeability contrast since, as argued above, a single pressure field exists at the local scale.

In this work, granular pumice stone is modeled as a collection of identical spherical porous grains of radius r_p and inter-granular void porosity ϕ_p . The inner structure of the pervious grains is modeled as an array of cylindrical pores of radius r_m and microporosity ϕ_m , with the total porosity being calculated as $\phi = \phi_p + (1 - \phi_p)\phi_m$. Thus, the model developed in [11], which makes use of that published in [23], is applied to the acoustic modeling of the studied granular pumice stone. The specific expressions for $\mathcal{K}_l$ and $\mathcal{C}_l$ (with $l = p, m$) are provided in Appendix A.

The effective parameters, Equations (1) and (2), allow determining the characteristic impedance Z_c and effective wave number k_c of the fluid equivalent to the double-porosity granular material via (with η being the dynamic viscosity of air)

$$Z_c(\omega) = \sqrt{\frac{\eta}{j\omega\mathcal{K}(\omega)\mathcal{C}(\omega)}}, \quad (3)$$

and

$$k_c(\omega) = \omega \sqrt{\frac{\eta\mathcal{C}(\omega)}{j\omega\mathcal{K}(\omega)}}, \quad (4)$$

respectively.

The normal-incidence frequency-dependent surface impedance $Z_w(\omega)$, pressure reflection coefficient $R(\omega)$, and sound absorption coefficient $\alpha(\omega)$ of a rigidly backed layer of thickness d are classically given by

$$Z_w(\omega) = -jZ_c(\omega) \cot(k_c(\omega)d), \quad (5)$$

$$R(\omega) = \frac{Z_w(\omega) - Z_0}{Z_w(\omega) + Z_0}, \quad (6)$$

and

$$\alpha(\omega) = 1 - |R(\omega)|^2, \quad (7)$$

respectively, where Z_0 is the characteristic impedance of the gas adjacent to the layer. In particular, the theoretically predicted sound absorption coefficient α will be compared with measured data below.

In summary, the sound absorption coefficient α for normal incidence (a descriptor to be measured as explained below) is given by Equation (7). This term depends on the reflection coefficient R , given by Equation (6). In turn, the reflection coefficient depends on the surface impedance Z_w of the rigidly backed layer of thickness d (see Equation (5)). The characteristic impedance Z_c and effective wave number k_c (see Equations (3) and (4)) are used to calculate the surface impedance. These two intrinsic effective parameters, that is, Z_c and k_c , require knowledge of the dynamic viscous permeability $\mathcal{K}$ and compressibility $\mathcal{C}$ for their calculation. The dynamic viscous permeability is given by Equation (1), while the effective compressibility is given by Equation (2). The former depends on the dynamic viscous permeability associated with the intergranular voids and that of the pores in the grains, which are, respectively, denoted as $\mathcal{K}_p$ (see Equation (A1)) and $\mathcal{K}_m$ (see Equation (A3)). The effective compressibility depends on that of the intergranular voids $\mathcal{C}_p$ (see Equations (A4) and (A5)) and that of the pores in the grains $\mathcal{C}_m$ (see Equations (A6) and (A7)), as well as the function

$\mathcal{F}$ given by Equation (A9) (see also Equation (A8), which provides the expression for the inter-scale pressure diffusion function).

2.2. Experimental Approach

The pumice stones used in this study were collected from rivers and lakes in southern Chile, in areas directly impacted by the last major volcanic eruption of the Caulle volcano in 2011. After drying, the raw rocks were crushed and transformed into a fine aggregate, which was then sieved for different sieve openings to produce a granular medium with controlled granulometry. Figure 1 shows a photo of the material before and after this transformation.



Figure 1. Photographs of a raw pumice stone before and after crushing.

The study classified the pumice samples into three distinct grain size ranges, i.e., (A) greater than 2.36 mm, (B) 2 to 2.36 mm, and (C) 1 to 2 mm (sieves No. 8, 10, and 18, following the specifications of ASTM E11 [25]).

The samples were carefully poured into a cylindrical container of known volume. The sample bulk densities were calculated by dividing the sample weight, measured with an analytical balance (US Solid, model USS-DBS15-3), by the known volume. The same procedure was followed with pumice dust to estimate the density of the pumice's solid frame.

The airflow resistivity of each sample was determined in the laboratory using the ISO-standardized method [26]. In this method, a layer of a given thickness of the material is subjected to a known low-velocity laminar airflow passing through it. The device for measuring airflow resistivity is based on the design presented by Iannace et al. [27]. It consists of a long cylindrical tube made of polymethylmethacrylate in which a saltwater piston produces an average steady airflow velocity, u , ranging from 0.5 to 40 mm/s. The volumetric flow is finely controlled by a set of valves. The average airflow velocity is measured by an electronic stopwatch connected to three sensors mounted at fixed distances of 3 cm apart along the tube wall. The sensors detect the passing of the saltwater surface column, and a microcontroller calculates the velocity based on the time it takes for the column to travel between the sensors.

A cylindrical measurement cell of a cross-sectional area of $2 \times 10^{-6} \text{ m}^2$, with a usable depth of up to 10 cm, contains the sample, which rests on a grid made of thin wires. A differential manometer (UEI model EM201B, accuracy of $\pm 1\%$ of the reading value) measures the air pressure difference, Δp , across the sample of known thickness d with respect to the atmosphere. The airflow resistivity is calculated as $\sigma = \Delta p / ud$. The entire device was calibrated according to the specifications outlined in the standard [26] and in reference [27].

Different samples of the granular pumice were poured on a melamine foam (Basotect) of thickness $d_m = 20 \text{ mm}$, which was placed in the sample holder of the airflow resistivity

measuring device. This layer of melamine foam served as the bottom substrate. A separate measurement was carried out on the melamine layer without the pumice sample to measure the controlled value of the melamine foam's airflow resistivity, σ_m . The foam was carefully cleaned with a vacuum cleaner before and after each measurement. The tests were repeated five times on samples of each type of pumice grain size to determine the average values of airflow resistivity. Figure 2 shows a picture of the different pumice samples placed in the sample holder of the airflow resistivity measuring device.

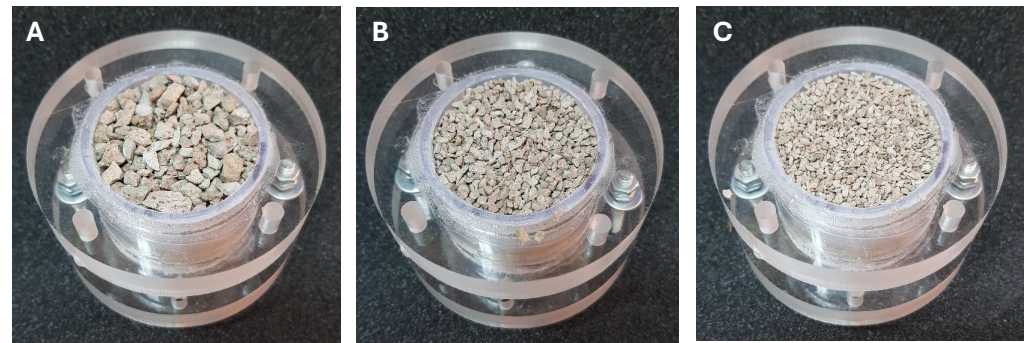


Figure 2. Pumice samples sieved for different sieve openings and poured in a sample holder: (A) greater than 2.36 mm, (B) 2 to 2.36 mm, and (C) 1 to 2 mm.

Using this approach, the airflow resistivity of the pumice sample, σ_g , of thickness d_g , is determined as

$$\sigma_g = \sigma_T \frac{L}{d_g} - \sigma_m \frac{d_m}{d_g}, \quad (8)$$

where $L = d_m + d_g$, and σ_T is the measured airflow resistivity of the melamine and pumice sample combined.

The normal-incidence frequency-dependent surface impedance, pressure reflection coefficient, and sound absorption coefficient of each rigidly backed sample were experimentally obtained using the standard two-microphone method [28]. This technique is a widely used, standardized measurement procedure, for which the reader is referred to the standard for details.

The measurements were carried out in a vertically positioned impedance tube. The tube has a circular cross-section and is made of a 1 1/4 inch SCH-80 steel tube (ASTM A106 grade B) with an external diameter of 42.2 mm, thickness of 4.85 mm, and nominal internal diameter of 32.5 mm. Its upstream part has a length of 70 cm, and the sample holder is 10 cm long.

Two 1/4-inch laboratory-grade microphone systems (PCB Piezotronics 378A14) were mounted flush with the tube walls. A distance of 20 mm separated the microphones. A data acquisition system (chassis NI DAQ 9174, input module NI 9234, and output module NI 9260) was used to acquire the sensed data. The system also sent an output signal to a BSWA PA300 power amplifier, which fed the full-range driver (AIYIMA, 53 mm diameter, 4 Ohm, 15 W maximum power, 82 dB of sensitivity) of the impedance tube's loudspeaker box. Linear sine sweep signals (initial frequency of 50 Hz, end frequency of 6000 Hz, and 10 s in duration) were employed in all the measurements. The data acquisition and processing were carried out with in-house software controlled by a notebook.

The sound absorption coefficient measurements were conducted under specific environmental conditions: atmospheric pressure and an average temperature of $101,292 \pm 124$ Pa and 24.2 ± 1.6 °C, respectively. Figure 3 shows a picture of the measurement setup.

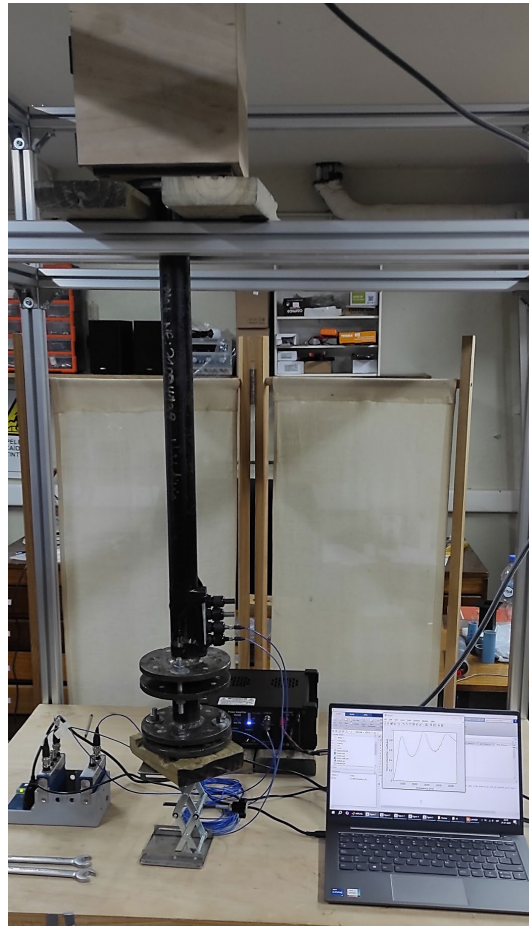


Figure 3. Measurement setup: a vertically mounted impedance tube and data acquisition system.

The material was poured to a fixed thickness in the sample holder. Experiments were conducted to obtain the acoustic descriptors of hard-backed layers of granular pumice stones with different thickness values, as shown below.

3. Results and Discussion

Table 1 shows the average results of the bulk density of each pumice sample of different grain size ranges. The density measurement was repeated five times for each sample, with the granules in the sample holder completely removed between repeats. To estimate the density of the solid phase in the porous material, the average density for the compacted pumice dust was measured to be $969.12 \pm 11.69 \text{ kg/m}^3$.

Table 1. Average results of the bulk density of each pumice sample.

Label	Grain Size, mm	Density, kg/m^3
A	>2.36	383.45 ± 7.85
B	2.0–2.36	397.98 ± 9.26
C	1.0–2.0	393.68 ± 16.13

The experimental results of airflow resistivity of each pumice sample, σ_g , are shown in Table 2. As explained in the methodology section, σ_g was determined from Equation (8) using a layer of melamine foam (Basotect) as the bottom substrate. The measured airflow resistivity of the foam without the pumice sample was $\sigma_m = 13.36 \pm 2.36 \text{ kPa s/m}^2$.

Table 2. Average of the airflow resistivity of the granular pumice stone samples.

Label	Grain Size, mm	Airflow Resistivity, kPa s/m ²
A	>2.36	5.3507 ± 0.3714
B	2.0–2.36	7.0546 ± 0.8071
C	1.0–2.0	7.8314 ± 1.0161

Characterization

A constrained best-fitting routine was implemented, with the aid of the differential evolution optimization method [11], to obtain the independent input parameters of the double-porosity model. This routine minimizes the square of the difference between the measured and predicted real and imaginary parts of the reflection coefficients. The effective particle radius r_p , the porosity of the inter-granular voids ϕ_p , the radius of the inner-grain pores r_m , and the porosity of the inner grain ϕ_m are the results of such a routine. Their values are summarized in Table 3.

Table 3. Input parameters of the double-porosity model for the pumice stone samples.

Label	r_p , mm	ϕ_p	r_m , μm	ϕ_m
A	1.21	0.3482	22.58	0.3668
B	1.04	0.3421	26.58	0.5571
C	0.82	0.3682	25.23	0.5402

Figure 4 shows the sound absorption coefficient of a rigidly backed 6 cm thick layer of granular pumice stone sample A. Good agreement is obtained between the measured and predicted sound absorption coefficient. The plot also shows that the sound absorption coefficient of a hypothetical layer of pumice stone sample A but with non-porous grains, a case named single porosity in the plot, is very different. Indeed, it is clear that it would not be possible to predict the experimentally observed acoustic behavior if one were to ignore the inner-grain porous structure of granular pumice stones and that the presence of said pores significantly contributes to enhancing sound absorption.

The influence of the thickness of the layer on the sound absorption coefficient of rigidly backed layers of the granular pumice stone sample B is shown in Figure 5. As expected, a thicker layer provides higher low-frequency sound absorption. The plot also highlights that the double-porosity model correctly captures the experimentally observed behavior. Furthermore, the sound absorption coefficient of a 4 cm thick layer of sample B is comparable to that of a 6 cm thick layer of sample A, which is consistent with the known fact that granular materials with smaller grain tend to be more efficient sound absorbers.

Figure 6 shows the sound absorption coefficient of hard-backed layers of the granular pumice stone sample C. Once again, the double-porosity model effectively predicts the measured sound absorption coefficient. However, there is a slight discrepancy above the first absorption peak. We note that the values of r_p and ϕ_p obtained with the constrained best-fitting routine provide a predicted flow resistivity that falls within one standard deviation of the mean of the measured value. In contrast, slightly higher values of predicted flow resistivity, obtained with lower values of r_p or higher ϕ_p , can lead to better agreement between predicted and measured sound absorption coefficient. This suggests that different compaction conditions of the grains during the measurements of flow resistivity and sound absorption coefficient may have been achieved, leading to comparable but not identical flow resistivity and, ultimately, to the slight discrepancy between the measured and predicted sound absorption coefficient.

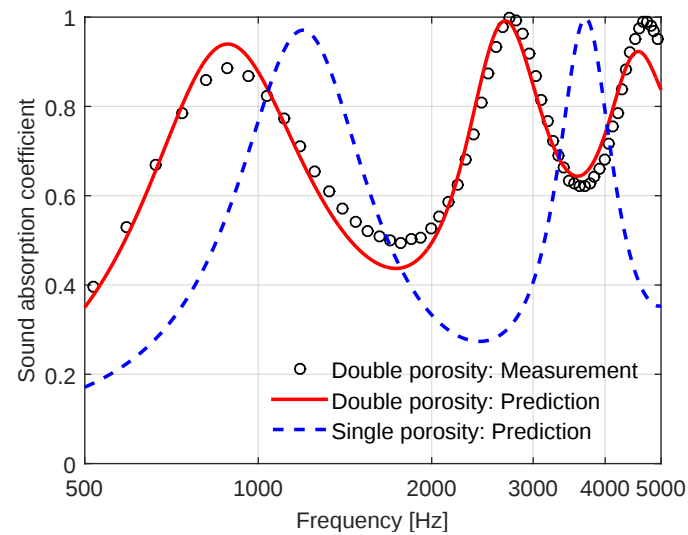


Figure 4. Measured and predicted sound absorption coefficient of a rigidly backed layer of pumice stone sample A. The nominal layer thickness is 6 cm. The predictions for a hypothetical material with the same mesoscopic characteristics than the pumice stone sample A but no inner-grain pores is shown as ‘single porosity’.

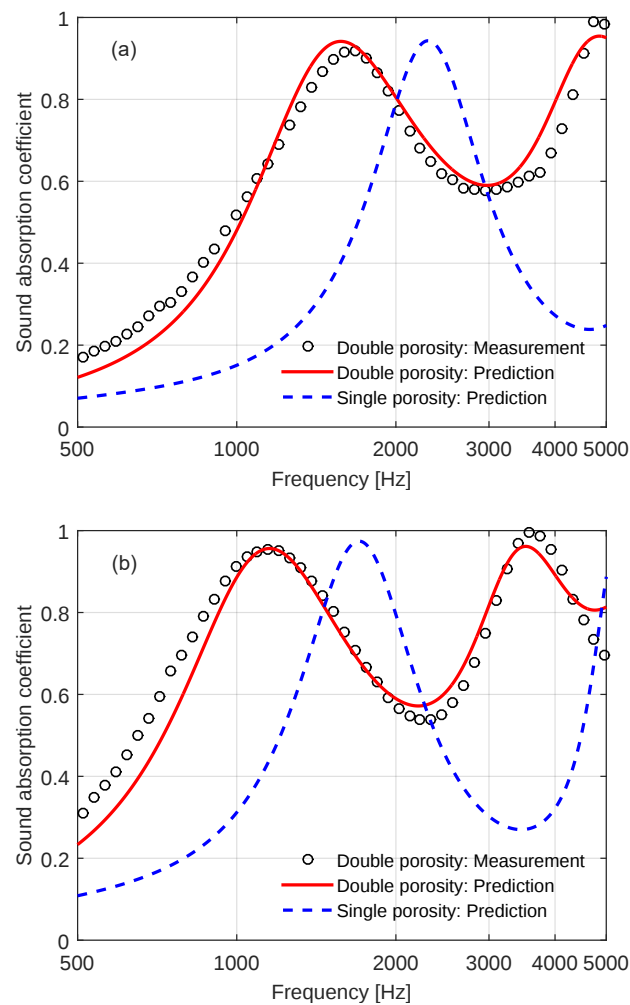


Figure 5. Measured and predicted sound absorption coefficient of rigidly backed layers of pumice stone sample B for two different layer thickness values: (a) 3 cm; (b) 4 cm. Markers—measurement. Continuous line—double-porosity model. Dashed line—single-porosity model.

Finally, it should be noted that the obtained values for the inner grain micropore radii are comparable (with an average value of $\bar{r}_m = 24.79 \pm 2.03 \mu\text{m}$), which is also the case for the microporosity of samples B and C. However, the microporosity of sample A is lower, which suggests that some of the micropores within this larger-grain sample A are not connected to other micropores that are in contact with the voids formed between the grains.

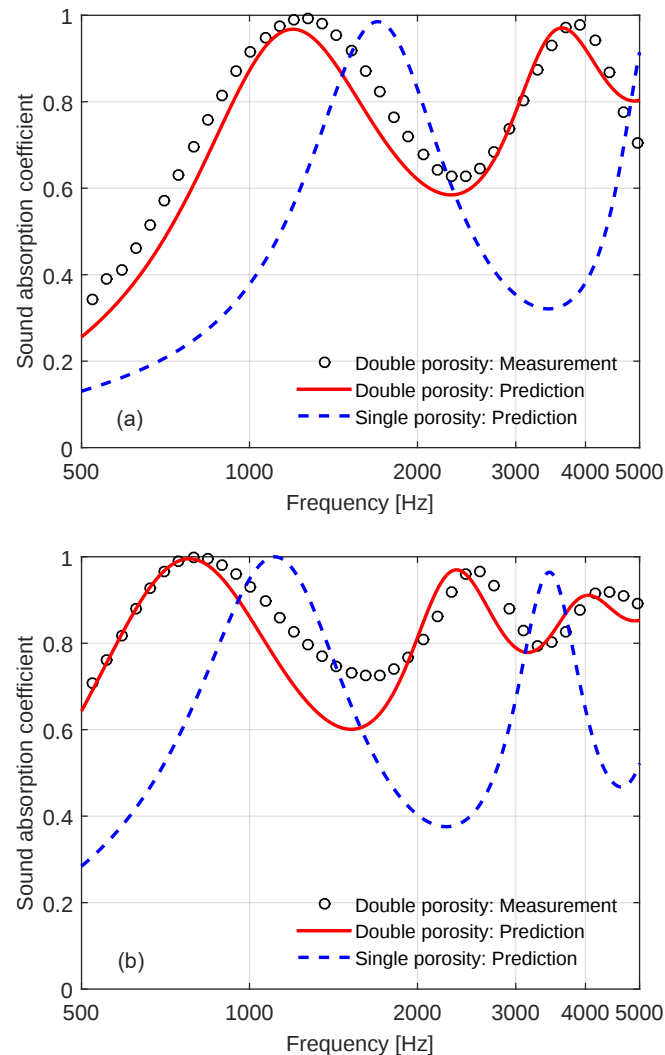


Figure 6. Measured and predicted sound absorption coefficient of rigidly backed layers of pumice stone sample C for two different layer thickness values: (a) 4 cm; (b) 6 cm. Markers—measurement. Continuous line—double-porosity model. Dashed lines—single-porosity model.

4. Conclusions

Although pumice performance as an aggregate for cementitious materials has been extensively studied, its sound absorption properties have received little attention. In this work, it has been shown that pumice has interesting properties as a sound-absorbing material. First, pumice mining is environmentally friendly compared to other materials, and its use could be a more sustainable alternative to traditional materials. According to the latest USGS report [29], all pumice mining is conducted through open pit methods in remote areas far from major population centers. As a result, the environmental impact is minimal and usually limited to relatively small geographic areas. The report also indicates that transportation costs determine the maximum economic distance for shipping pumice, yet it remains competitive with alternative materials. Further research must assess the

exact environmental impact of granular pumice through systematic life cycle analysis to accurately compare it with alternative materials.

Second, pumice is a naturally occurring multiscale porosity material with a microporous medium significantly contributing to the attenuation of sound waves. Therefore, it exhibits higher sound absorption at low frequencies than a solid-grain material with the same mesoscopic characteristics at a reduced weight. It is concluded that the sound wave propagation in pumice can be accurately described by a double-porosity model, something that the single-porosity model cannot do. Thus, granular pumice could be an alternative loose material for filling membrane absorbers and cavity resonators [30], increasing average room sound absorption and reducing unwanted reverberation. Materials that may be substituted for pumice include activated carbon, expanded clay, zeolite, vermiculite, and granulated aerogels [31].

The results suggest further research in stratified double-porosity granular pumice media, which could lead to obtaining an optimized multilayer sound-absorbing material. In this study, we have considered dry pumice, so the potential effects of moisture were neglected. Following the authors' previous work [32], future research will explore how hygroscopic effects affect its sound absorption properties. Another topic for future studies is evaluating the acoustic properties of a consolidated pumice-based material under high-temperature conditions. Since these stones result from volcanic processes, they withstand heat effectively, making them suitable for application in industrial silencers, for example.

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Appendix A

The mathematical expressions of the double-porosity model [11,33] are recalled here. We model a double-porosity material as an array of identical porous spheres of radius r_p and inter-granular void porosity ϕ_p . The pores in the grains are modeled as an array of cylindrical micropores with radius r_m and porosity ϕ_m .

The dynamic viscous permeability associated to the inter-granular voids is given by

$$\mathcal{K}_p(\omega) = -j(1 - \beta^3)\delta_v^2 \left(1 - \frac{\beta^3}{1 - \beta^3} \frac{\varsigma \frac{1 - \beta^3}{\beta^3} + 1}{\varsigma - 1} \right), \quad (\text{A1})$$

where $\varsigma = \frac{3}{z^2} \frac{A_p z + B_p \tanh(z(\beta - 1))}{a_p z + b_p \tanh(z(\beta - 1))}$, $A_p = (3 + (\beta z)^2) \left(1 + \frac{z^2}{6} \right) - 3\beta \left(1 + \frac{z^2}{2} \right)$, $a_p = \frac{1}{3} (3 + (\beta z)^2) - 3\beta - \frac{2}{\beta} \left(1 + \frac{z^2}{6} \right) + \frac{4}{\cosh(z(\beta - 1))}$, $B_p = (3 + (\beta z)^2) \left(1 + \frac{z^2}{2} \right) - 3\beta z^2 \left(1 + \frac{z^2}{6} \right)$, $b_p =$

$3 + \beta(\beta - 1)z^2 - \frac{2}{\beta}\left(1 + \frac{z^2}{2}\right)$, $\beta = \sqrt[3]{1 - \phi_p}$, $z = j^{1/2} \frac{r_p}{\beta \delta_v}$, and $\delta_v = \sqrt{\frac{\eta}{\rho_0 \omega}}$. Here, η is the dynamic viscosity of air and ρ_0 is its density.

It is noted that the static value of this parameter is given by

$$\mathcal{K}_{p0} = \frac{r_p^2}{3\beta^2} \left(\frac{2 + 3\beta^5}{\beta(3 + 2\beta^5)} - 1 \right). \quad (\text{A2})$$

The viscous permeability of the inner-grain pores is given by (with $X_v = j^{3/2} \frac{r_m}{\delta_v}$)

$$\mathcal{K}_m(\omega) = -j\phi_m \delta_v^2 \left(1 - \frac{2}{X_v} \frac{J_1(X_v)}{J_0(X_v)} \right). \quad (\text{A3})$$

The effective dynamic compressibility and thermal permeability of the inter-granular voids are given by

$$\mathcal{C}_p(\omega) = \frac{\phi_p}{P_0} \left(1 - j\omega \rho_0 c_p \frac{\gamma - 1}{\gamma} \frac{\Theta_p(\omega)}{\phi_p \kappa} \right), \quad (\text{A4})$$

$$\Theta_p(\omega) = -j(1 - \beta^3) \delta_t^2 \left(1 - \frac{\beta}{1 - \beta^3} \frac{3}{z_t^2} \left(1 - \beta z_t \frac{1 + z_t \tanh(z_t(\beta - 1))}{z_t + \tanh(z_t(\beta - 1))} \right) \right) \quad (\text{A5})$$

where $z_t = j^{1/2} \frac{r_p}{\beta \delta_t}$ and $\delta_t = \sqrt{\frac{\kappa}{\rho_0 c_p \omega}}$. The physical parameters are the specific heat capacity ratio γ , thermal conductivity κ and specific heat capacity at constant pressure c_p of air.

The effective dynamic compressibility and thermal permeability of the inner-grain pores are given by (with $X_t = j^{3/2} \frac{r_m}{\delta_t}$)

$$\mathcal{C}_m(\omega) = \frac{\phi_m}{P_0} \left(1 - j\omega \rho_0 c_p \frac{\gamma - 1}{\gamma} \frac{\Theta_m(\omega)}{\phi_m \kappa} \right), \quad (\text{A6})$$

$$\Theta_m(\omega) = -j\phi_m \delta_t^2 \left(1 - \frac{2}{X_t} \frac{J_1(X_t)}{J_0(X_t)} \right). \quad (\text{A7})$$

The inter-scale (inter-granular voids to/from grains) pressure diffusion function is given by

$$B(\omega) = -j(1 - \phi_p) \delta_b^2 \left(1 - 3\zeta_b^{-2} (1 - \zeta_b \cot(\zeta_b)) \right), \quad (\text{A8})$$

where $\zeta_b = j^{3/2} \frac{r_p}{\delta_b}$, $\delta_b = \sqrt{\frac{\mathcal{B}_{app}}{\omega}}$, and $\mathcal{B}_{app}(\omega) = \frac{\mathcal{K}_m(\omega)}{\eta \mathcal{C}_m(\omega)}$. The expression for $B(\omega)$ above is used to determine the function $\mathcal{F}(\omega)$ in Equation (2). The latter is given by

$$\mathcal{F}(\omega) = 1 - \frac{j\omega B(\omega)}{(1 - \phi_p) \mathcal{B}_{app}(\omega)}. \quad (\text{A9})$$

References

1. Arenas, J.P.; Asdrubali, F. Eco-materials with noise reduction properties. In *Handbook of Ecomaterials*; Martínez, L.M.T., Kharissova, O.V., Kharisov, B.I., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 3031–3056.
2. Schiavoni, S.; Bianchi, F.; Asdrubali, F. Insulation materials for the building sector: A review and comparative analysis. *Renew. Sustain. Energy Rev.* **2016**, *62*, 988–1011. [\[CrossRef\]](#)
3. Mohanta, N.R.; Murmu, M. Alternative coarse aggregate for sustainable and eco-friendly concrete—A review. *J. Build. Eng.* **2022**, *59*, 105079. [\[CrossRef\]](#)
4. Tanyildizi, M.; Gökalp, I. Utilization of pumice as aggregate in the concrete: A state of art. *Const. Build. Mater.* **2023**, *377*, 131102. [\[CrossRef\]](#)
5. Hossain, K.M.A. Development of volcanic pumice-based cement and lightweight concrete. *Mag. Concr. Res.* **2004**, *56*, 99–109. [\[CrossRef\]](#)
6. Cifci, D.I.; Meric, S. A review on pumice for water and wastewater treatment. *Desalin. Water Treat.* **2016**, *57*, 18131–18143. [\[CrossRef\]](#)
7. Rashad, A.M. A short manual on natural pumice as a lightweight aggregate. *J. Build. Eng.* **2019**, *25*, 100802. [\[CrossRef\]](#)

8. Olny, X.; Boutin, C. Acoustic wave propagation in double porosity media. *J. Acoust. Soc. Am.* **2003**, *114*, 73–89. [\[CrossRef\]](#)
9. Barguet, L.; Romero-García, V.; Jiménez, N.; Garcia-Raffi, L.M.; Sánchez-Morcillo, V.J.; Groby, J.-P. Natural sonic crystal absorber constituted of seagrass (*Posidonia Oceanica*) fibrous spheres. *Sci. Rep.* **2021**, *11*, 711. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Pompoli, F. Acoustical characterization and modeling of sustainable *Posidonia* fibers. *Appl. Sci.* **2023**, *13*, 4562. [\[CrossRef\]](#)
11. Venegas, R.; Umnova, O. Acoustical properties of double porosity granular materials. *J. Acoust. Soc. Am.* **2011**, *130*, 2765–2776. [\[CrossRef\]](#)
12. Fleischer, C.A.; Zupan, M. Mechanical performance of pumice-reinforced epoxy composites. *J. Compos. Mater.* **2010**, *44*, 2679–2696. [\[CrossRef\]](#)
13. Sevinc, A.H.; Durgun, M.Y.; Eken, M. Taguchi approach for investigating the engineering properties of concretes incorporating barite, colemanite, basaltic pumice and ground blast furnace slag. *Const. Build. Mater.* **2017**, *135*, 343–351. [\[CrossRef\]](#)
14. Sultan, M.A.; Gaus, A.; Hakim, R.; Imran. Review of the flexural strength of lightweight concrete beam using pumice stone as of substitution partial coarse aggregate. *Int. J. Geomate* **2021**, *21*, 154–159. [\[CrossRef\]](#)
15. Mahmoud, H.A.; Tawfik, T.A.; Abd El-razik, M.M.; Faried, A.S. Mechanical and acoustic absorption properties of lightweight fly ash/slag-based geopolymer concrete with various aggregates. *Ceram. Int.* **2023**, *49*, 21142–21154. [\[CrossRef\]](#)
16. Onoue, K.; Tamai, H.; Suseno, H. Shock-absorbing capability of lightweight concrete utilizing volcanic pumice aggregate. *Const. Build. Mater.* **2015**, *83*, 261–274. [\[CrossRef\]](#)
17. Sariisik, A.; Sariisik, G. New production process for insulation blocks composed of EPS and lightweight concrete containing pumice aggregate. *Mater. Struct.* **2012**, *45*, 1345–1357. [\[CrossRef\]](#)
18. Canbolat, S.; Kut, D.; Dayioglu, H. Investigation of pumice stone powder coating of multilayer surfaces in relation to acoustic and thermal insulation. *J. Ind. Text.* **2015**, *44*, 639–661. [\[CrossRef\]](#)
19. Bozkurt, T.S.; Demirkale, S.Y. Investigation and development of sound absorption of plasters prepared with pumice aggregate and natural hydraulic lime binder. *Appl. Acoust.* **2020**, *170*, 107521. [\[CrossRef\]](#)
20. Soyaslan, I.I. Thermal and sound insulation properties of pumice/polyurethane composite material. *Emerg. Mater. Res.* **2020**, *9*, 859–867. [\[CrossRef\]](#)
21. Kapicová, A.; Bílý, P.; Fládr, J.; Seps, K.; Chylík, R.; Trtík, T. Development of sound-absorbing pervious concrete for interior applications. *J. Build. Eng.* **2024**, *85*, 108697. [\[CrossRef\]](#)
22. Giraldo, J.R.; Colorado, H.A. Evaluation of noise mitigation by different materials and balcony configurations in urban street canyon facades: Casework in Aburrá Valley, Colombia. *J. Arch. Eng.* **2024**, *30*, 04024012.
23. Boutin, C.; Geindreau, C. Estimates and bounds of dynamic permeability of granular media. *J. Acoust. Soc. Am.* **2008**, *124*, 3576–3593. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Arenas, J.P.; Rebolledo, J.; Nuñez, G.; Venegas, R. Sound absorption characterization of pumice stone. In Proceedings of the 29th International Congress on Sound and Vibration, Prague, Czech Republic, 9–13 July 2023.
25. ASTM E11-24; Standard Specification for Woven Wire Test Sieve Cloth and Test Sieves. ASTM International: West Conshohocken, PA, USA, 2024.
26. ISO 9053; Acoustics—Determination of Airflow Resistance, Part 1: Static Airflow Method. International Organization for Standardization: Geneva, Switzerland, 2018.
27. Iannace, G.; Ianniello, C.; Maffei, L.; Romano, R. Steady-state air-flow and acoustic measurement of the resistivity of loose granular materials. *J. Acoust. Soc. Am.* **1999**, *106*, 1416–1419.
28. ISO 10534; Acoustics—Determination of Acoustic Properties in Impedance Tubes, Part 2: Two-Microphone Technique for Normal Sound Absorption Coefficient and Normal Surface Impedance. International Organization for Standardization: Geneva, Switzerland, 2023.
29. Crangle, R.D. Pumice and Pumicite. In *Mineral Commodity Summaries*; U.S. Department of the Interior and U.S. Geological Survey: Washington, DC, USA, 2024; pp. 140–141.
30. Arenas, J.P.; Marin, V.; Venegas, R. Membrane sound absorber with a granular activated carbon infill. *Appl. Acoust.* **2023**, *202*, 109180. [\[CrossRef\]](#)
31. Begum, H.; Horoshenkov, K.V.; Conte, M.; Malfait, W.J.; Zhao, S.; Koebel, M.M.; Bonfiglio, P.; Venegas, R. The acoustical properties of tetraethyl orthosilicate based granular silica aerogels. *J. Acoust. Soc. Am.* **2021**, *149*, 4149–4158. [\[PubMed\]](#)
32. Venegas, R.; Parra, C.C.; Cuevas, V.; Alarcón, E.; Rebolledo, J. Hygroscopic effects on sound absorption of multiscale bio-based porous materials. In Proceedings of the INTER-NOISE 2024, Nantes, France, 25–29 August 2024.
33. Venegas, R.; Boutin, C.; Umnova, O. Acoustics of multiscale sorptive porous materials. *Phys. Fluids* **2017**, *29*, 082006.

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