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Characterizations of acoustical porous media: standardized methods, current trends and challenges

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Understanding and predicting the vibro-acoustic behavior of acoustical porous materials (like foams, synthetic or natural fibers, metamaterials…) requires to determine the parameters of their solid and their fluid phases. This work presents an non-exhaustive overview of the methods commonly used to assess the visco-elastic and acoustic parameters of such acoustic porous media. A first part is dedicated to identify the parameters related to the dissipation in the fluid phase while a second part focuses on the identification of the parameters related to the solid phase (also called the skeleton). The perspectives related to the characterization of acoustical porous media are also depicted, particularly in the context of recent and ongoing standardization developments.

KEYWORDS

characterization, porous media, acoustic, visco-elastic, parameters

1 Introduction

Traditionally, 2 types of characterization are considered for an acoustical porous material: the acoustic one related to its fluid phase and the elastic (or more rigorously viscoelastic) one related to its solid phase (also called the skeleton of the porous medium). These 2 characterizations can be considered as independent in some cases, while in general they are not, since the fluid phase can influence the solid behavior and *vice versa*. The seminal work by M. A. Biot is often used to account for the coupling between these 2 phases (Biot, 1956a; Biot, 1956b, Biot, 1962; Allard and Atalla, 2009; Jaouen, 2025a).

The acoustic parameters of the fluid phase, for an isotropic material, are those required to compute its dynamic mass density ρ_{eq}, describing the visco-inertial dissipative effects, and its dynamic bulk modulus K_{eq}, describing its thermal dissipative effects. Alternatively, the characteristic impedance $Z_c = \sqrt{\rho_{eq} K_{eq}}$ and the characteristic wavenumber $k_c = \omega\sqrt{\rho_{eq}/K_{eq}}$ (ω denotes the pulsation or angular frequency) can be used without separating the dissipative effects. For example, a Johnson-Champoux-Allard-Lafarge (JCAL) model (Johnson et al., 1987; Champoux and Allard, 1991; Lafarge et al., 1997) requires the knowledge of the six following parameters to compute ρ_{eq} and K_{eq} (see Figure 1).

1. The open porosity ϕ (usually simply named as "porosity"),
2. The static air-flow resistivity σ (in N.s.m^{-4}) or the static viscous permeability $k_0 = \eta/\sigma$ (in m^2) where η is the dynamic viscosity of the fluid phase (in N.s.m^{-2}),
3. The high frequency limit of the dynamic tortuosity α_∞ (its name is usually simplified to "tortuosity"),

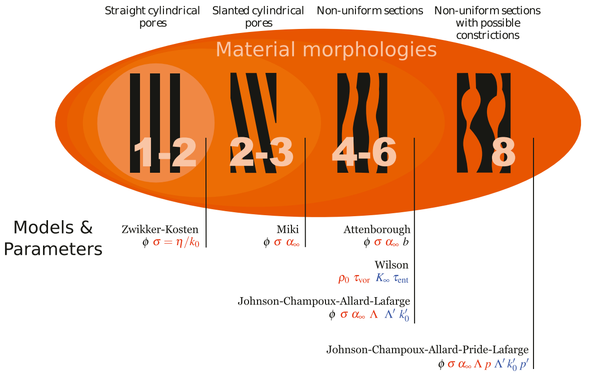

FIGURE 1
Schematic representation of profiles of pore networks and models that can be used to describe these morphologies. The more complicated the morphology, the more parameters are required. In blue: parameters related to the visco-inertial dissipation effects and in red: the parameters of the thermal dissipation effects.

4. The viscous characteristic length Λ (in m),
5. The thermal characteristic length Λ' (in m),
6. The static thermal permeability k_0' (in m^2).

The elastic parameters of the solid phase are, again for an isotropic material, its mass density ρ its Young's modulus E, its loss factor (sometimes refered to as its structural damping) and its Poisson's ratio ν.

The model involving the 6 JCAL parameters discussed for the fluid phase above and the 4 elastic parameters above for the solid phase, i.e., 10 parameters in total, is referred to as the Biot-JCAL model.

Some models for the fluid phase require less than 6 parameters depending on the morphology assumption of the pore structure or the physical phenomena involved. As examples the Delany-Bazley-Miki (DBM) model (Delany and Bazley, 1970; Miki, 1990) only requires σ to compute ρ_{eq} and K_{eq}; the Johnson-Champoux-Allard (JCA) model (Johnson et al., 1987; Champoux and Allard, 1991) requires the first 5 parameters of a JCAL model (i.e., not accounting for the static thermal permeability).

Similarly, some models for the solid phase are derived from Biot equations with some simplifications. The limp model for a light material with a Young's modulus close to 0 (like a cotton candy) requires only the mass density ρ (Panneton, 2007). The rigid-body (Bécot and Sgard, 2006) (this reference, which discusses numerical simulations, is the only published article to date that clearly presents the difference between limp and rigid body models) for a light material with a Young's modulus that cannot be neglected, but which is set in motion by a sound excitation like a rigid body also requires only the mass desnity ρ. An example of rigid-body behavior can be obtained for polystyrene beads glued together. Note that the limp and rigid-body models for the solid phase of a material are sometimes confused, as the models are equivalent for large porosities.

Hence, other examples of models to describe the behavior of acoustical porous materials are: the limp-DBM or the rigid-body-JCA.

In the next sections of this document, we will focus on (i) the hypotheses used regarding the materials to be characterized, (ii) the characterization of the acoustic parameters of the fluid phase, (iii) the characterization of the elastic parameters of the solid phase, (iv) some general considerations regarding the characterization of acoustical porous media. This document cannot be exhaustive and does not aim to provide a complete review of the characterization methods but rather to give some guidelines.

2 Hypotheses

To characterize acoustical porous media, assuming they are composed of only 2 phases: a fluid and a solid, the following hypotheses apply.

- Both the fluid and solid phases are assumed to be continuous (so that the theory of continuous media can be applied to both phases)
- The pore size within the material is small compared to the wavelengths of the waves involved, ensuring that the material can be descibed by an Representative Elementary Volume (REV) and behaves as a homogeneous medium at the macroscopic level (Bensoussan et al., 1978; Auriault et al., 2010). Note that while ρ_{eq} and K_{eq} are defined for homogeneous materials, it is possible to quantify heterogeneities for acoustical porous media as John R. Willis did for non-homogeneous elastodynamic materials (Willis, 1981; Groby et al., 2021). The "Willis coupling factor" χ, proportional to the inverse of a velocity, equals 0 for homogeneous materials and differs from 0 for asymmetric materials/systems, or materials exhibiting non-local effects when the long-wavelength assumption (compared to the characteristic sizes of the materials) is no longer fulfilled [see e.g., Lafarge and Nemati (2013)].
- A no-slip condition as well as a thermodynamic equilibrium at the interface between the fluid and the solid phases are commonly assumed in most models. While this hypothesis is not mandatory, it reduces the number of parameters to be evaluated.

3 Characterization of the acoustic parameters

In this section, we focus on the characterization of the parameters related to the fluid phase and in particular to the parameters of the Johnson-Champoux-Allard-Lafarge (JCAL) model. Other models and parameters exist (see, e.g., Wilson (1993), Horoshenkov et al. (2019), but they can be expressed as those of the JCAL one (Jaouen, 2025b).

Note that the titles of some references mention the characterization of "acoustic and non-acoustic" parameters, following the request of some reviewers, in previous articles published by, e.g., Doutres et al. (2010), who argued that porosity, for example, is not a parameter used only in acoustics and therefore cannot be labeled as an acoustic parameter.

The techniques are divided into two distinct categories: direct measurements are those for which an analog or numerical signal can be directly correlated to the value of the parameter while indirect estimations are all other methods.

Only some of the acoustical parameters used to describe the visco-inertial and thermal behviors of acoustical porous materials are directly measurable. The open porosity, the static air flow resistivity and the high frequency limit of the dynamic tortuosity can be directly measured. The devices used in these cases are borrowed from science fields related to other porous materials (such as rocks) or are adapted from these other porous materials to acoustical ones (which have usually very large permeability and porosity compared to rocks).

The remaining part of the acoustical parameters $(\Lambda, \Lambda', k_0')$ are estimated via indirect measurements.

3.1 Direct measurements

Direct measurements were the first to be developed and are still commonly used today to double check the results of indirect estimations.

3.1.1 Static air-flow resistivity

The first parameter to be directly measured is the static air-flow resistivity σ. The method is based on the measurement of the pressure drop across a sample of known thickness and area. The flow resistivity is then calculated using Darcy's law. The method is standardized in ISO 9053-1 (International Organization for Standardization ISO, 2018).

3.1.2 Open porosity

The second parameter to be directly measured is the open porosity ϕ: the ratio of the volume of the pore network accessible to the acoustic wave to the total volume of the material.

A first method, for acoustical porous materials with porosity close to 1, was introduced by Beranek (1942) and was later improved or adapted [see, e.g., Champoux et al. (1991), Leclaire et al. (2003)]. The principle is to reduce the volume of an enclosure containing a material sample. Doing so, the pressure will increase in the enclosure compared to the atmospheric pressure. This increase in pressure depends on the volume of the enclosure and the volume accessible to the air inside the porous medium. By measuring the pressure increase it is possible to determine the open porosity of the material. This method is close to the one used for geomaterials called gas picnometer, detailed in various standards, which is based on the injection of a gas under pressure in the volume enclosure. One keypoint is that the larger the samples the more accurate will be the results.

An alternative technique is based on Archimedes' principle (Panneton and Gros, 2005; Salissou and Panneton, 2007): the porosity is measured by weighing a sample of known volume and then saturating it with a fluid of known density. Again, accurate measurements are obtained with large samples.

3.1.3 High-frequency limit of the tortuosity

Brown (1980), then Johnson et al. (1982) published methods for measuring the high frequency limit of the tortuosity from the determination of the electrical resistance at the extremities of a porous sample for which an electrically charged liquid has saturated the fluid phase.

One difficulty with these methods is saturating the sample, which can be difficult for materials with small pore sizes of a few microns or tens of micron, while these materials typically exhibit the highest tortuosity values. These methods, which are no longer in use, also require the skeleton of the tested material to be an electrical insulator and prior knowledge of the open porosity.

3.2 Indirect estimations

Indirect estimations are based on the measurement of one or more physical quantities in combination with a model (sometimes only its physical asymptotic limits).

Inverse methods are a large part of indirect estimations. There are two types of inversions: numerical and analytical. Numerical inversions are based on minimization techniques between a numerical simulation and at least one indicator such as the sound absorption coefficient, the surface impedance, the characteristic wavenumber... The estimation of more than two parameters usually relies on a multiple indicators to avoid local minima during the minimization step.

Analytical inversions rely on analytical expressions to identify the parameters.

3.2.1 Ultrasound frequencies approach

The tortuosity α_∞ can be assessed by measuring the speed of sound in a sample of known thickness and porosity. The tortuosity is then calculated using the speed of sound in air and the speed of sound in the sample. Allard et al. (1994) described the method in the frequency domain for ultrasound frequencies.

One keypoint of this method is that it is a quick method which was then used to mapped heterogeneity of material samples. One limit is however that at ultrasound frequencies, the multiple scattering phenomenon can appear in porous media with a characteristic pore size of hundreds of microns. This multiple scattering is not accounted for in classical visco-thermal dissipation models and require additional developments [see, e.g., Tournat et al., (2004)]. While trying to estimate more parameters (Λ, Λ') from ultrasound techniques in the frequency domain (Leclaire et al., 1996a) it was proposed to make successive measurements within 2 fluids to quantify and exclude the multiple scattering effects from the estimations of both the viscous and thermal characteristic lengths Λ and Λ' (Leclaire et al., 1996b).

Later, based on the work of Panneton and Only in the audible frequencies range, Groby et al. (2010) have proposed a method to extract ρ_{eq} and K_{eq} from a reflection and a transmission measurements (on the same porous smaple) at ultrasonic frequencies. From ρ_{eq} and K_{eq}, Groby et al. were thus able to estimate α_∞, Λ, Λ' and ϕ if this latter parmaeter was not used as an apriori.

Currently, high-frequency methods are being developed to estimate the parameters p and p' (or alternately α_0 and α_0') of models used to finely describe the behavior of materials with pores of non-uniform cross sections with possible constrictions [see, e.g., Roncen et al. (2019)].

3.2.2 Audible frequency approach

3.2.2.1 Whole frequency range

The first attempts to characterize the visco-inertial and thermal dissipation effects of porous media over audible frequency ranges were made by minimization techniques, in diffuse sound field, or more commonly in impedance tubes (with more controlled excitation, at plane waves and normal incidence) (International Organization for Standardization ISO, 2023). Then, analytical techniques were developed to assess the dynamic bulk properties ρ_{eq} and K_{eq} (or equivalently the characteristic impedance Z_c and the characteristic wavenumber k_c) from the measurements, in an impedance tube, of 2 samples with different thicknesses (Smith and Parrott, 1983) or 1 sample backed alternately with 2 cavities (Utsuno et al., 1989).

The impedance tube gained in popularity in the late 1990s when the process to extract ρ_{eq} and K_{eq} was simplified by using a third microphone inside the rigid backing to measure the pressure behind the sample, as described by Iwase and Izumi (1996); Iwase et al. (1998). This 3-microphone technique [for which clear analyses and easier references to find are Doutres et al. (2010), Salissou and Panneton (2010)] was used by Panneton and Olny (2006), Olny and Panneton (2008) to extract 4 of the JCAL parameters (α_∞, k_0', Λ, Λ') from an analytical inversion with the prior knowledge of ϕ and σ. This method was then extended to retrieve the 6 JCAL parameters from asymptotes (Jaouen et al., 2020) (as discussed in the next section).

Note that the 3-microphone technique is currently in the process of being standardized via ISO 10534-3 International Organization for Standardization (ISO) (proposition submitted).

A drawback of impedance tube methods is that the boundary conditions can influence the overall behaviors of ρ_{eq} and K_{eq} (Cummings, 1991; Pilon et al., 2004). Leakages around the material sample in the tube can create double-porosity effects (Olny and Boutin, 2003) for resistive materials which will modify ρ_{eq} and K_{eq}. Vibrations of the material skeleton (i.e., its solid phase) will also have impacts on the measured ρ_{eq} and K_{eq}. Thus, it is important to avoid or reduce such effects, with Teflon tape rather than wax concerning leakages or adding nails to the material sample as described in Iwase et al. (1998) (see Figure 2) to reduce or shift the frequencies of the skeleton resonances (or to extract the parameters from identified frequency ranges not affected with these skeleton vibrations). For low resistivity materials, fewer precautions are necessary as the influence of small leakages around the sample has a smaller effect on ρ_{eq} and K_{eq}, and this effect can be modeled (Verdière et al., 2013).

3.2.2.2 Asymptotic limits

The low-frequency limit of the imaginary part ($\Im$) of the dynamic mass density (ρ_{eq}) for a homogeneous, isotropic material with a motionless skeleton is proportional to the static air-flow resistivity: $\sigma = \lim_{\omega\to 0}\omega|\Im(\rho_{eq})|$ (the sign of ρ_{eq} is determined by the time convention: $\Im(\rho_{eq}) \leq 0$ for $\exp(+j\omega t)$ and $\Im(\rho_{eq}) \geq 0$ for $\exp(-j\omega t)$ hence the absolute value). The method, introduced by Panneton and Olny (2006) can be used to estimate σ or to perform a consistency check with a direct measurement. The method is now reported in the informative appendix of ISO 9053-1 (International Organization for Standardization ISO, 2018).

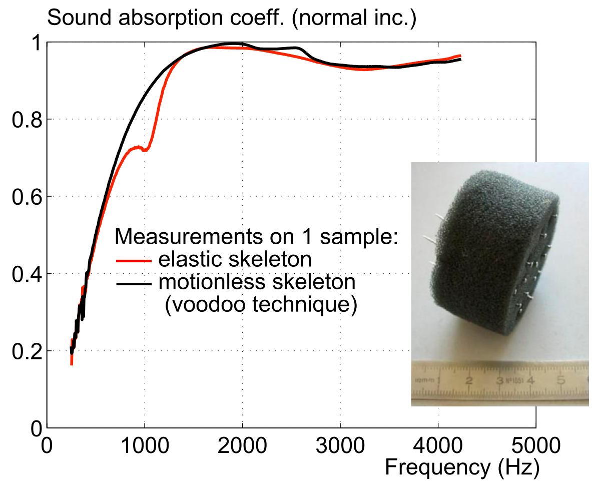

FIGURE 2
The "Voodoo" technique relies on adding nails to the material sample as described in Iwase et al. (1998) to reduce or shift the frequencies of the skeleton resonances.

The open-porosity can also be estimated from high and low frequency asymptotes. As an example, Jaouen et al. (2020) estimate the open porosity from the low and high frequency limits of the real part ($\Re$) of the dynamic bulk modulus (K_{eq}) for a homogeneous, isotropic material with a motionless skeleton: $\lim_{\omega\to 0}\Re e(K) = P_0/\phi$ and $\lim_{\omega\to+\infty}\Re e(K) = \gamma P_0/\phi$ (where γ is the ratio of the specific heats of the fluid saturating the porous material).

The drawback of these methods being the possible difficulty in identifying the asymptotes due to the limited spacing between the microphones at low frequencies, the diameter of the tube at high frequencies and possible vibrations of the skeleton of the porous sample.

3.2.3 Time domain methods

In the early 2000s, theoretical and experimental developments were also made in the time domain.

Fellah et al. (2003) presented a method for estimating the porosity and the tortuosity of a porous material sample from the reflected impulse waves. This method is limited to highly absorbing samples as it approximates the reflected waves as coming only from the first interface with air.

Two additional methods were developed a few years later to estimate the static air-flow resistivity from the reflected waves Sebaa et al. (2005) or the transmitted waves Fellah et al. (2006) depending on the resistance of the sample. Numerical inversions (i.e., minimization techniques) were used to extract the value of the air-flow resistivity with the prior knowledge of the porosity.

Measurements in the time domain and analysis in both the time and the frequency domains were used, for transmitted waves, to estimate σ without the a-priori knowledge of the porosity (Sadouki et al., 2014).

While the time domain approach is in a sparse state of development, it offers perspectives for complementary robust characterization methods.

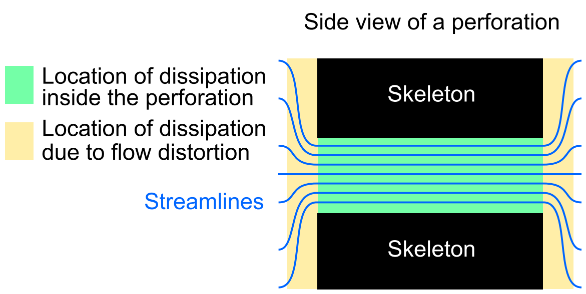

FIGURE 3
Length correction due to flow distortion for thin porous media. The smaller the perforation rate (i.e., the porosity), the larger the added dissipation.

3.2.4 Pore size distribution and microtomography

Less common methods for estimating the parameters of the fluid phase include measuring the material's Pore Size Distribution (PSD) or extracting its microstructure (at the Representative Elementary Volume) from 3D microtomography scans (Horoshenkov et al., 2016, Horoshenkov et al., 2019; Perrot et al., 2012; Chevillotte et al., 2013).

The pore size distribution is usually obtained by typical methods such as mercury intrusion into the pore network. 3D microtomography acquisitions being expensive, 2D images are usually preferred with the added difficulty of capturing the third dimension which can result in inaccurate microstructure dimensions or large uncertainties about these dimensions, and hence inaccurate or uncertain material parameters.

From the microstructural information extracted by one or the other method, the parameters of a Johnson-Champoux-Allard-Lafarge model or even a Johnson-Champoux-Allard-Pride-Lafarge model (Pride et al., 1993) with 2 additional low-frequency parameters usually denoted as p and p' (or alternately α_0 and α_0') can be calculated (Perrot et al., 2008).

3.3 A note about thin porous media

The acoustic characterization of facing screens or perforated plates, typically with a thickness of a few millimeters or less, has been less addressed. Like Maa between the 1970s and the 1990s (Maa, 1975; Maa, 1998; Atalla and Sgard, 2007), in 2007, used the models developed for thicker porous media (Atalla and Sgard benefited from an update of the models to the JCA and JCAL ones compared to Maa) while adding a correction to account for the flow distortion around the pores or perforations (see Figure 3). The associated length correction Jaouen and Chevillotte (2018) introduces additional viscous dissipation that is not negligible compared to the viscous dissipation occurring within the pores or perforations themselves.

Based on Atalla and Sgard model (Jaouen and Bécot, 2011), developed an inverse analytical method to estimate the independent parameters required from the measurements of the thin porous material backed by a cavity in an impedance tube.

3.4 Work in progress and perspectives

The methods presented in the previous sections still require attention, as some subtleties remain. For example, at ultrasonic frequencies, it is not always easy to determine whether scattering effects are involved. In the impedance tube, dealing with the limp, rigid body or, more generally, the motion or vibration of the skeleton can also be challenging.

Some work is still in progress to characterize the materials in different environments or conditions (and the references given up to the next section do not all refer to characterization, but sometimes to models, as no characterization is yet known to the authors). For example, at high temperature (for muffler or thermo-acoustic applications) (Debray, 2000; Di Giulio et al., 2024), at high pressure (Aurégan and Pachebat, 1999; Temiz et al., 2016; Chevillotte et al., 2017), with a fluid phase partially or totally saturated with water (for building and underwater applications) Chabriac et al., 2016; Gourlay et al., 2017), with flow (for aviation or appliance applications), *in-situ* (for end-of-chain applications).

On a different note, while the main dissipation phenomena are the same for all materials (including, for example, materials with inner quarter-wavelength or Helmholtz resonators): visco-inertial, thermal and structural damping in the skeleton, some techniques are being developed to handle the specificities of multiple dynamics, aka "metamaterials". Examples of materials for which developments are in progress include: activated carbon exhibiting a sorption phenomenon (making it impossible to measure porosity directly) (Castillo, 2011; Bechwati et al., 2012; Shen and Jiang, 2014; Venegas and Umnova, 2016) natural fibers which typically exhibit multiple scales of porosity (as were the materials manufactured using the first 3D printing technologies but this tendency is decreasing as printing precision improves), as well as materials with fractal microstructures (Jaouen and Olny, 2005; Fellah et al., 2021); nanomaterials for which it can be difficult to manufacture prototype samples with a number of cells large enough to have dimensions suitable for testing using impedance tubes or ultrasound techniques.

As reported above, standardization methods are trying to adapt to these new methods and new materials at a faster pace than ever before (International Organization for Standardization, 2025). They also provide a more critical and informative approach to some techniques, as in the case of ASTM E2611-2019 (ASTM International, 2019) and a possible future ISO 10534-4 International Organization for Standardization (ISO) (proposition to be submitted) (4 microphones), by explaining the fundamental differences between diffuse field transmission measurement on large samples and impedance tube transmission measurement on small samples (International Organization for Standardization, 2024).

4 Characterization of the elastic parameters

Most of the experimental methods used to characterize visco-elastic parameters (Young's moduli, loss factors and Poisson's ratios) are adaptations of techniques used for polymers or metal (Gibson and Ashby, 1997; Corsaro and Sperling, 1990; Hilyard and Cunningham, 1994) (note that the terms elastic and visco-elastic parameters are used interchangeably to refer to the parameters of the solid phase). Modifications of existing devices are usually made to account for the interaction between the two phases of an acoustical porous material or to account for specific ranges of values for these acoustical porous materials. Young's moduli and loss factors of acoustical materials range from approximately 10^0 to 10^9 N.m^{-2} and from approximately 10^{-2} to 1 respectively.

A wide variety of methods exist to characterize the visco-elastic parameters of the solid phase of porous materials. They are typically divided into different categories according to their frequency regime: static/quasistatic or dynamic and their vibration nature: uniaxial compression, torsion, bending. . .

An almost exhaustive list was given in Jaouen et al. (2008) and is still relevant today. Interlaboratory tests have followed [see, e.g., Bonfiglio et al. (2018), Chevillotte et al. (2020)]. Thus this work will not enumerate all the methods, but will emphasize several key features.

From interlaboratory tests, large deviations were observed between the values of the elastic parameters obtained by different methods. The main deviations were coming from the frequency range and the initial condition (imposed load or imposed strain).

The uni-axial compression [in the quasistatic regime Langlois et al. (2001) or in the dynamic one as described in, e.g., (International Organization for Standardization ISO, 1989; Bonfiglio and Pompoli, 2015)], on cubic or short cylindrical samples, is probably the most common method used (due to its apparent simplicity). By examining the difficulties of such methods, it is possible to highlight the critical aspects of viscoelastic characterization of porous materials.

Apart from the issues of cutting and positioning the material sample in the test bench, the uni-axial compression methods is influenced by factors such as.

1. The possible anisotropy of the material,
2. The environment conditions and in particular the temperature and the frequency (as these factors can significantly influence the elastic moduli and their loss factors),
3. The static strain or stress dependence of the material,
4. The coupling with the fluid phase (as air enters and leaves the sample during the compression test)

Point 1, the anisotropy, is particularly important for fibrous materials as the elastic parameters in the direction of the fibers can differ significantly from those in perpendicular directions. Successive uni-axial compression tests on 3 different axes (assuming they are the principal axes of the materials) only provide estimations of the elastic parameters.

Point 2, the temperature and frequency dependence is illustrated in Figure 4. Visco-elastic materials (compared to elastic materials) exhibit strain and energy dissipations that are time-dependent. This time dependence implies a frequency dependence as well as a temperature dependence according to the Time-Temperature Superposition (TTS). This point is particularly important for a material with a polymer skeleton, since its glass transition temperature (or frequency) is usually (designed to be) between −20 and 20°C (or a few Hz to a few thousand Hz). While visco-elastic models evolve with mathematical tools such as fractional derivatives, commonly involving between 5 and 7 parameters (Dinzart and Lipiński, 2010; Gourdon et al., 2015), it can be observed that there are still few characterizations made at different temperatures and frequencies.

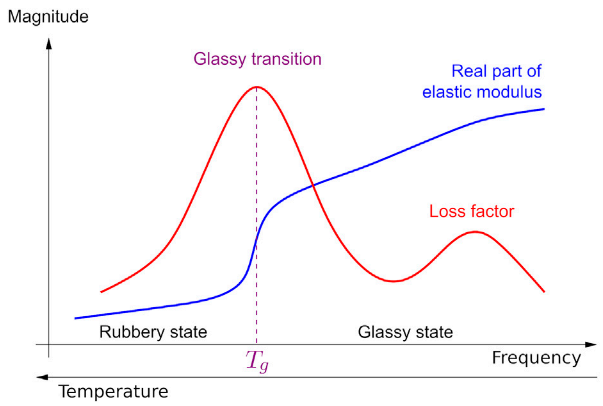

FIGURE 4
Schematic representation of the evolution of a complex modulus with time and frequency as per the Time-Temperature Superposition (TTS) principle or more rigoursly here its frequency representation.

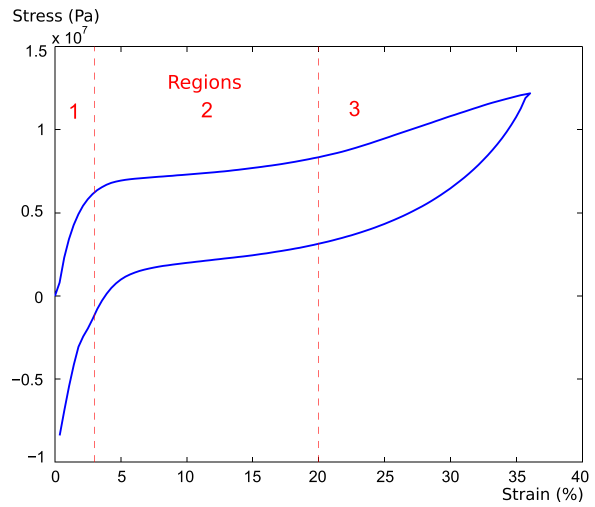

FIGURE 5
Strain vs stress measurement of a foam showing a hysteresis behavior. Region 1 is a linear bending region, region 2 is the buckling region, region 3 is the densification region where the foam behaves as a solid material after the cells have collapsed.

Point 3, the static strain or stress dependence is illustrated in Figure 5. Estimation of the visco-elastic parameters requires, or at least is much easier, to be in region 1 of Figure 5, where the linear visco-elastic theory can be applied. It is worth noting that only a few studies on the hysteresis effect in porous materials have been carried out (Guyer et al., 1997; Gusev and Aleshin, 2002) and this field of research is still wide open. Point 3 highlights the fact that it is necessary for the rigorous experimenter to perform a strain-stress measurement before the actual visco-elastic characterization. It is noteworthy that there is no linear range for fibers, due to their microstructures, which reinforces the fact that the static strain or stress used during the tests should be reported and adapted to the application in which the material will be used. An additional difficulty with the dynamic uni-axial compression method (based on the resonance of a mass-spring system, the porous sample playing the role of a heavy spring) is that the frequency range and the static stress and strain are not independent.

Point 4, the coupling with the fluid phase, has been studied by a few authors including Kraak (1959) [and discussed further in Schmelzer et al. (2021)] and Danilov et al. (2004). In his work, W. Kraak has proposed a correction to the measurement of the elastic properties of the material sample based on the transverse resistivity of the material (i.e., in a direction perpendicular to the axis of compression). This correction is currently considered to be included in an ongoing revision of ISO 9052-1 (International Organization for Standardization ISO, 1989). Danilov et al. on the other hand have pointed out the importance of staying at low frequencies (below 50–100 Hz) to avoid a significant influence of the fluid phase on the results of the elastic characterization.

Once these first 4 points have been addressed, it remains to estimate the complex Young's modulus and possibly the Poisson's ratio, assuming an isotropic material. Indeed, the test result for the uni-axial compression test on a material is the complex stiffness of the material sample (a function of its complex Young's modulus, Poisson's ratio and dimensions). Some authors refer to the "apparent Young's modulus", another quantity derived from the stiffness. The apparent Young's modulus is equal to the Young's modulus only when the Poisson's ratio is 0 [i.e., for fibrous materials without specific surface or bulk treatment Tarnow, 2005; Berthelot, 1999]. In all the other cases, a difficult direct measurement of the Poisson's ratio from a transverse displacement is required, or alternatively and most commonly, 2 samples with different shape factors must be tested to determine the Young's modulus and the Poisson's ratio using a pre-computed abacus (Sim and Kim, 1990; International Organization for Standardization ISO, 2011).

For materials with higher Young's moduli and lower porosity, the cantilever beam as described in ASTM E756 (ASTM International, 2005) and ISO 6721-3 (International Organization for Standardization ISO, 2021) (homogeneous, damped on one side, i.e., the Oberst's beam, damped on both sides, i.e., the modified Oberst's beam, or the sandwich beam) is a more suitable technique. Again, the estimation of the Young's modulus (in the axis of the beam) and its associated loss factor can be a difficult task depending on the studied frequency range, the thickness of the porous material and thus the required hypotheses regarding the shear and the compression in the deflection direction for the porous material.

While tentatives were made to characterize the elastic parameters from impedance tube measurements, the results were not always reliable due to the lack of control over the boundary conditions. Even for thin materials, backed by an air-gap, where a clamped boundary condition can be guaranteed at the periphery with the tube, the difficulty is to identify the bending modes before estimating the elastic parameters. In addition, there is a difference in stresses between an impedance tube and common elastic characterization techniques. A sound pressure of 80 dB is a weak excitation causing a low stress for the specimen under test, a stress often smaller than the one required to be in the linear stress-strain zone when exciting only the skeleton of the material during, e.g., an uni-axial compression (the stress being only sufficient for a surface stimulation of the "hairs" of the sample).

Methods based on guided wave measurements (Allard et al., 2005; Boeckx et al., 2005b; Boeckx et al., 2005a; Glorieux et al., 2014) on specimens with dimensions of 1 square meter or more have also been studied. The size of the samples together with the numerical and experimental works needed to extract the elastic parameters were the main limitations of these methods, which have not seen any new developments for a decade.

5 General considerations

This section presents some general considerations that apply to both the acoustic and elastic characterizations.

- Uncertainties in measurements and characterizations are now regularly reported, improving the reliability of the results (see e.g., Horoshenkov et al. (2007), Pompoli et al. (2017), Gaborit et al. (2020).
- Anisotropy remains a slowly growing area of research (Melon et al., 1998; Göransson et al., 2009; Guastavino, 2008; Cuenca and Göransson, 2012; Van der Kelen and Göransson, 2013) despite its importance for some materials (in particular fibrous) and for some conditions like mechanical excitations (Tran-Van, 2004) (in French) (Parra Martinez et al., 2016). The primary challenge lies in the increased number of parameters required compared to isotropic materials (σ, α_∞, Λ, E, η, ν are becoming tensors).
- Statistical approaches (in particular Bayesian methods) and Machine Learning algorithms are more and more used to identify and correct errors in measurement data (Chazot et al., 2012; Roncen et al., 2018; Stender et al., 2021; Gaborit and Jaouen, 2023; Chevillotte, 2024). The commercial availability of material databases has significantly improved the efficiency and applicability of these algorithms, allowing for more accurate predictions in the characterizations of materials.

6 Conclusion

Both acoustic and elastic characterizations of porous media remain active fields of research with adaptations of methods to new challenges such as materials with multiple dynamics, more complex environment conditions with high temperature or flow...

While numerous methods are available, certain points still require attention.

- On the acoustic side, the low-frequency parameters p and p' (or alternatively α_0 and α_0') remain difficult to characterize, while the low frequency range is of tremendous importance for sound absorbing materials.

- On the elastic side, broadband frequency characterization remains the exception rather than the rule while polymers exhibit noticeable frequency-dependent behaviors.
- On both sides, the research on anisotropy is notably sparse while fibrous materials, that exhibit noticeable anisotropy (such as natural or recycled synthetic fibers) are becoming more common.

Standardization is evolving faster than ever to keep up with recent developments. Newly published standards try to be more critical and informative about the methods and try to remain open to the development of new methods to meet the challenges of new materials and applications.

Finally, it is important to keep in mind that no method can be considered perfect. A combination of complementary methods often provides the most robust and comprehensive results and the words of Tamas Pritz provide an insightful reminder of the importance of simplicity in methodological development: "Some works suggest that the curiosity of the methods is more important than the results... In my opinion, the simpler the method, the better to have reliable results."

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