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COMPILATION OF REFERENCE VALUES IN SELECTED POROUS MATERIALS FOR SOUND PROPAGATION IN FINITE ELEMENT MODELLING

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ABSTRACT

Porous materials currently used in the building industry require to have a high performance in terms of sound insulation and absorption. In reality, each material is characterized differently for each application, focusing on the properties important for each matter. This has led to having a nonuniform collection of data for each material. In this paper the information collected from the available literature has been arranged to suit a finite element model of porous materials, with the purpose of analysing the absorption coefficient and other acoustical behaviours of the materials. By considering the reported properties, plus estimating the missing not-characterized values, the model is completed, and results are compared between porous materials.

Keywords: *porous materials, equivalent fluid, literature research, finite element modelling*

1. INTRODUCTION

In acoustics, some types of porous materials, like foams or mineral wools, are used for both sound absorption and sound insulation applications. The models that describe the sound propagation range from simple empirical models that require one parameter [1] to more intricate models with more than eight parameters that can be difficult to characterize [2–5]. The most complex model presented in this paper is a poroelastics model, which takes into account properties related to the structural part of a porous material, properties such as mass density, stiffness and damping. Simpler models might struggle with delivering accurate results in the low or high frequency range [6, 7], therefore there is an interest for explaining the wave propagation through a complete model, as complex as it may be. Depending on the research area and application within acoustics, the parameters are characterized in a porous material vary. This has led to a vast amount of literature around the same type of material, where each contribution characterizes different parameters. This makes it difficult to find literature where all the acoustic and elastic parameters of a specific material sample are characterized. If a source is missing some parameters, there is a need to seek the information for the missing parameters in a different study that uses the same type of material. In the case of the aforementioned acoustic models for sound propagation, it can be a problem if the data comes from more than one source, since the reliability of the model decreases. Added to that, it is known that the measurement methods vary between laboratories and also the reproducibility of the results can be unreliable [8]. This leads to having a high uncertainty in the data that would be used in the model. To reduce the uncertainty it is useful to compare the model with other consistent models commonly used, as well as with reported experimental results.

In this paper, a literature search is done to gather the data from different sources for three different material types: melamine foam, glass wool and stone wool. The compiled data is used on the transmission line theory and numerical finite element models of Delany-Bazley-Miki, Johnson-Champoux-Allard and Biot, to get the absorption coefficient for each material. With each material, the re-

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sults are compared between the used models to validate their consistency, besides a comparison with experimental results from the source articles. The Method chapter explains shortly the theory for the models used, followed by the process for extraction and organization of data from the literature; then the details for implementation of the models as simulations and a description of a sensitivity study made to understand the impact of each parameter on the model's results, are explained. Finally, different results between models for each type of material along with their sensitivity studies are presented and discussed. This work is the basis of a more complex project that intends to understand the effect of anisotropic parameters of a porous material in its acoustic performance [9].

2. METHOD

The types of materials used in these models are in general anisotropic, and the mineral wools are not homogeneous. To simplify the process of gathering data from literature as well as the use of the models, it will be assumed that the materials are all isotropic and homogenous. In further work the anisotropy for acoustic and elastic parameters will be taken into account to understand its role in the models' results [9].

The normal incidence sound absorption coefficients of each material were modelled through a fully empirical model, the Delany-Bazley-Miki (DBM) [1] model; a semi phenomenological equivalent fluid model, the Johnson-Champoux-Allard (JCA) [5, 10] model, and a diphasic model, the Biot [2] model. The models deliver bulk properties such as the characteristic impedance Z_c of the material and the complex wavenumber k, or the equivalent density ρ_{eq} and bulk modulus K. These bulk properties are then used to calculate the normal incidence sound absorption coefficients α. These results were compared with the experimental results reported in the papers where the data was gathered from. The measured data from the papers was obtained by digitizing the reported plots through a web plot digitizer tool [11].

2.1 Porous material models

The Delany-Bazley model is an empirical model, which was created based on measuring the sound absorption of glass fibre and mineral wool materials, where all the materials had a porosity value close to 1 [1]. The model requires the airflow resistivity r, and has reliable results as long as the relation between the frequency and the airflow resistivity belong to a specific range ($0.01 < f/r < 1.00$). It computes the characteristic acoustic impedance and the complex wave number. In this model, the resulting real part of the surface impedance can become negative at low frequencies. Miki [1] proposed a modification to the Delany-Bazley model for the impedance and bulk modulus, satisfying the positive-real impedance property as well as the property of causality.

Table 1. Porous material parameters needed for each of the simulation models. Left to right: airflow resistivity, porosity, tortuosity, viscous characteristic length, thermal characteristic lenght, density, Young's modulus, Poisson ratio, loss factor.

DBM	r								
JCA	r	ϕ	α_∞	Λ	Λ'	ρ			
Biot	r	ϕ	α_∞	Λ	Λ'	ρ	E	ν	η
Unit	[Pa s m^{-2}]	ϕ	α_∞	[m]	[m]	[kg m^{-3}]	[Pa]		

The JCA model [5, 10] is used to describe the viscous and thermal dissipative effects. The model requires five parameters: porosity ϕ, static airflow resistivity r, tortuosity α_∞, viscous characteristic length Λ, and thermal characteristic length Λ'. This model describes the equivalent density and the bulk modulus as functions of these acoustic parameters. A correction from Lafarge [4] was done to this model so the low frequency results are more accurate, although permeability k'_0 should be characterized for that. In this study the JCA model is used [5, 10] and the thermal permeability is not required for this model.

The Biot model [2] considers the interaction between a solid and a fluid phase, e.g. the mineral wool and the air, respectively. The theory assumes that there is a coupling between the two phases, unlike the previous model which assumes that the skeleton is motionless. Considering the solid phase means that the elastic parameters of the material (Youngs modulus E, shear modulus G, Poisson ratio ν, and loss factor η) play a role on the wave propagation. In the Biot model the behavior is described through coefficients of elasticity including a potential coupling coefficient, which indicates how much influence does one phase has over the other.

The material parameters needed for each model are presented in Table 1.

2.2 Data compilation

A literature search was done to gather data about the acoustic and elastic parameters of the three types of materials: melamine foam, glass wool and stone wool.

Melamine foam is a common material that has been thoroughly investigated and characterized [5, 12–14], making it a good option to use as a reference for testing the models. A similar situation exists for glass wool, which is a common material to find in literature regarding mineral wool [1, 5, 15]. These materials are used in this paper to verify and confirm the reliability of the models, where after the model is expected to also work well for stone wool, for which data is not easily found in literature.

Most of the literature selections shown in this paper were chosen because they include measured sound absorption results, most of the required parameters, and also the thermal permeability k_0' of the materials, a parameter that will be considered in future work when using the Johnson-Champoux-Allard-Lafarge model (JCAL) [4].

The gathered data was organized in Table 2 by material and author. The information that one source lacked was completed with another source, considering that the materials were as similar as possible in the parameters they share, most commonly density, porosity, and thickness.

Kino and Ueno's work [16] compared melamine foam and glass wool, and reported a characterization of these types of materials to get the parameters for the JCA model; this means it only showed the fluid parameters, therefore the elastic parameters had to be gathered from other sources to complete the Biot model. Zai et. al [14] reported the same parameters and values for melamine foam as Kino [16], plus the elastic parameters. It was not stated that the parameters were characterized by them. They reported sound absorption measurements of the material with three different thicknesses plus simulations in COMSOL Multiphysics using the JCA model. Rénault et. al [17] measured damping and stiffness of melamine foam and used an estimation method for the Poisson ratio. Tran-Van and Olny [15] measured and reported the elastic parameters for glass wool considering its transverse isotropy, the parameters selected for this paper were the ones measured in the normal direction, as in the model setup. However, the transverse values are important for further investigations regarding the anisotropy of mineral wools [9]. Lei, Chazot and Dauchez [13] showed the acoustical and elastic parameters from a thin compressed glass wool sample, the acoustic and elastic parameters were measured by them. In another publication from the same authors [18], regarding melamine foam and glass wool, they reported data for all the parameters required for the Biot model, except the Young's modulus. They studied the change of the parameters after compression, so a wide variety of sets of data are available for different thicknesses and densities of the same sample. Nennig et. al [19] measured the acoustic parameters reported, and estimated and assumed some elastic values in their work with transversely isotropic glass wool. As for stone wool, Bécot and Jaouen [12] worked on a double porosity composite that includes a stone wool sample and a melamine foam sample, for which they reported all the necessary parameters characterized in their laboratories. Blinet et. al [20], characterized ceiling panels that included stone wool and thus measured and reported the parameters on the separate layers of a panel. However, some acoustic parameters such as porosity, tortuosity, viscous and thermal characteristic lengths and Poisson ratio were assumed and there is no reference to where they obtained these values from.

2.3 Wave propagation and absorption models

Two software programs were used for modelling: MATLAB [21], using plane wave transmission line theory to perform a DBM and Biot simulation, and COMSOL Multiphysics [22], using the finite element method (FEM), was used for a DBM, JCA and Biot simulation. In all cases, normal incidence is assumed as well as homogeneous isotropic materials.

2.3.1 The DBM in MATLAB and COMSOL

The code in MATLAB for the DBM model was obtained from the APMR [23] site where the only parameters needed are the thickness and airflow resistivity. The sound absorption coefficient was calculated by obtaining the impedance using the complex impedance and wavenumber calculated with the model as $Z = -jZ_c/\tan(kh)$, and calculating the reflection coefficient and substracting it to get the absorption coefficient as $\alpha = 1 - (Z - \rho_0 c_0)/(Z + \rho_0 c_0)$.

As for the COMSOL implementation, an impedance tube scenario was modelled by having a cylindrical geometry of 0.10 m diameter and 0.30 m length of air with sound hard boundaries, simulating the impedance tube and referred to as the air domain, where the pressure acoustics node was used. The porous domain had the same diameter and also sound hard boundaries in the walls and the back end of the tube plus no air gap after the porous domain. The thickness of the porous sample varied depending on the used data. The poroacoustics node was used in the porous domain, and the DBM poroacoustics model was chosen where the porous matrix properties include the Miki constants. The absorption coefficient was calculated in the same way in all COMSOL simulations: by comparing the incident and outgoing power at the ”entrance” of the tube as $\alpha = 1 - (P_{out}/P_{in})$.

2.3.2 The JCA model in COMSOL

The configuration and geometry was the same as the DBM model, and in the chosen poroacoustics model (JCA) the porous matrix approximation was set to rigid, the other options were kept default.

2.3.3 The Biot model in MATLAB and COMSOL

The Biot model in MATLAB was obtained from APMR [24]. The code considers an homogeneous isotropic sample and calculates the equivalent density and bulk modulus of the material with the JCAL [4] model to then calculate the characteristic impedances and wavenumbers for the two phases through the Biot theory. The code was modified to use JCA instead of JCAL, and the modification was made in equation **??**, where the dependence on the thermal permeability k_0' was changed to the thermal characteristic length Λ' [5]. The absorption coefficient was then calculated through the output impedance $\alpha = 1 - (Z - \rho_0 c_0)/(Z + \rho_0 c_0)$.

The Biot model in COMSOL was implemented by using the poroelastic waves node on the porous domain. The Biot model with thermal and viscous losses was selected as well as a drained matrix, isotropic configuration. Regarding the boundary conditions, three scenarios were simulated. First a sample clamped to the tube walls, to include the resonance effects that can be observed in impedance tube measurements under such mounting conditions [25]. Afterwards, a roller or sliding boundary condition was added, which constrains the displacement only in a direction normal to the boundary. This simulated a scenario where there sample can vibrate freely inside the tube. Finally, a scenario with a sample with periodic boundary conditions for an infinitely large sample was implemented using Floquet periodicity.

2.4 Sensitivity study

A sensitivity study was carried out to understand the impact that the change in a parameter will have in the absorption coefficient. This showed to what parameters, the system was more prone to change and led to conclusions around which parameter data could be safely assumed or estimated and which ones had to be carefully characterized.

This study was inspired by the work of Sadri et al. [26]. The sensitivity elements S_i, were obtained by changing each one of the material parameters in the system, denoted θ_i, for an infinitesimal amount and leaving the rest of the parameters as they originally were. The resulting absorption coefficient was compared to the original, and a ratio of the change in the absorption coefficient to the change in the parameter resulted on the sensitivity of the system to that specific parameter.

$$S_i = \frac{\partial \alpha}{\partial \theta_i} \approx \frac{\alpha(\theta_i + \Delta\theta_i) - \alpha(\theta_i)}{\Delta\theta_i} \tag{1}$$

The sensitivity was then normalized by multiplying with the original values for the absorption coefficient and the parameter to obtain $\hat{S}_{ij} = S_{ij}\theta_j/\alpha_i$. The sensitivity study was done for the center frequency of each octave band between 63 Hz and 16k Hz.

3. RESULTS

3.1 Melamine foam

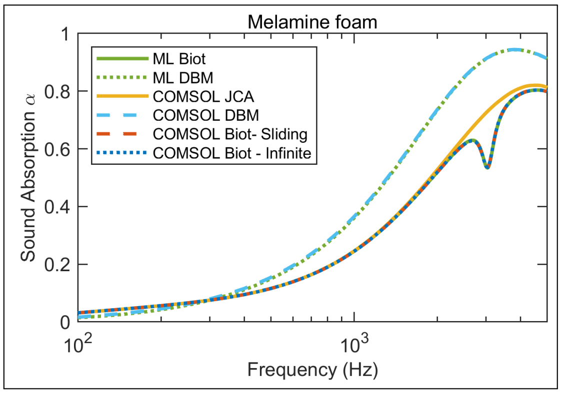

Figure 1. Results for melamine foam F1, Table 2.

The information for melamine foam was mainly gathered from [14], where the only missing parameters were the loss factor, thus obtained from [17]. The data can be seen in the top table in Table 2. The results shown here correspond to the F1 sample from the table.

For all the materials, the transmission line theory implemented in MATLAB (ML Biot), was compared against the JCA model (COMSOL JCA) the Biot model in COMSOL with clamped boundary conditions (COMSOL Biot-Clamped),a model that assumes an infinitely large sample (COMSOL Biot-Infinite), and a model that assumes sliding boundary conditions (COMSOL Biot - Sliding). The comparisons are divided into Figs. 1 and 2 to make it easier to distinguish the curves. In Fig. 1 only three lines can be distinguished clearly because some results overlap as they were expected to. ML-DBM overlaps with COMSOL-DBM. And the same happens for the ML Biot, COMSOL Biot-Infinite, and COMSOL Biot-Sliding, confirming that the transmission line theory and the FEM model coincide. The JCA model is closer to the Biot models, away from the empirical DBM ones, except for the dip that the Biot models show. Fig. 2 shows the results from the same sample, comparing COMSOL Biot-Clamped, COMSOL Biot-Sliding (same result as the ML-Biot transmission line result), and the experimental measurements from [14]. The results agree quite well. The difference at the lower frequencies is expected, because of the inaccuracy from the JCA approach used on the Biot model, missing the effects that the JCAL model include through the thermal permeability k_0' parameter. The dip seen around 3,050 Hz can be explained by the structural phase vibration that is not considered in the JCA model or the DBM models. The difference of the dip's location is due to the Poisson ratio, which is related to the solid phase, a better fit to the experimental results happens when considering a Poisson ratio of 0.438. It can be seen in Fig. 2 that the Poisson ratio is one of the most sensitive parameters along with the porosity and the thermal characteristic length. The latter is related to results in lower frequencies, which explains the discrepancy in the lower frequencies between experimental results and the simulations. It can be seen in Fig. 2 that the COMSOL results of the clamped sample also include the dip, but it is not so prominent and this is due to the boundary conditions considered and directly related to the value of the loss factor η. The dip's characteristics depend explicitly on the elastic parameters. The difference on the size of the dip between the measured and simulated results might be due to the fact that the loss factor was obtained from another publication [17], and due to uncertainty of the actual boundary condition in the measurements [14].

3.2 Glass wool

The data acquired for the glass wool is presented in the middle table in Table 2. For the G1 sample, the missing values were taken from G2. The samples G3 and G4 were simulated separately but still the values for the Poisson ratio and the thermal permeability had to be assumed and taken from other authors [18,28]. The G3 sample has the most reliable data set due to all the information comes

Table 2. Samples used in this paper are marked in bold. Top table: Melamine Foam data compilation. Values obtained from [14, 17] Middle table: Glass wool data compilation. Values obtained from [13, 15, 16, 18, 19] Bottom table: Stone wool data compilation. Values obtained from [12, 20, 27].
* Poisson's ratio is assumed to be zero for fibrous materials as in [28]. ** The thermal permeability values are obtained from another source according to similar densities in [18]. ***Value adapted from [27].

Mel. Foam	**F1** [14]	F2 [14]	F3 [14]	F4 [17]
Parameter				
h [mm]	**25.0**	50.0	75.0	19.4
ϕ	**0.995**	0.995	0.995	
r [Pa s m^{-2}]	**10,500**	10,500	10,500	
α_∞	**1.0059**	1.0059	1.0059	
Λ [μm]	**240**	240	240	
Λ' [μm]	**470**	470	470	
ρ [kg m^{-3}]	**9**	9	9	8.73
E [MPa]	**180**	180	180	132.4
ν	**0.46**	0.46	0.46	0.33
k_0' [nm^2]	**1.5**	1.5	1.5	
η				0.08

Glass wool	G1 [16]	G2 [15]	**G3** [19]	G4 [13]
Parameter				
h [mm]	25.0		**50.8**	0.0684
ϕ	0.99		**0.98**	0.90
r [Pa s m^{-2}]	16800		**38000**	150500
α_∞	1.01		**1.0**	1.1
Λ [μm]	132		**295**	20
Λ' [μm]	237		**708**	34
ρ [kg m^{-3}]	31.8	25.0	**16.0**	165.0
E [MPa]		3400	**0.670**	460
ν	0*	0*	**0***	0*
k_0' [nm^2]	2.6**		**6.3****	1**
η		0.21	**0.1**	0.008

Stone wool	S1 [20]	**S2** [12]
Parameter		
h [mm]	19.5	**39**
ϕ	0.9	**0.97**
r [Pa s m^{-2}]	70600	**88400**
α_∞	1.6	**1.01**
Λ [μm]	60	**190**
Λ' [μm]	150	**480**
ρ [kg m^{-3}]	100	**160**
E [MPa]	398	**1375**
ν	0*	**0***
k_0' [nm^2]	0.148***	**1.00**
η	0.3	**0.3**

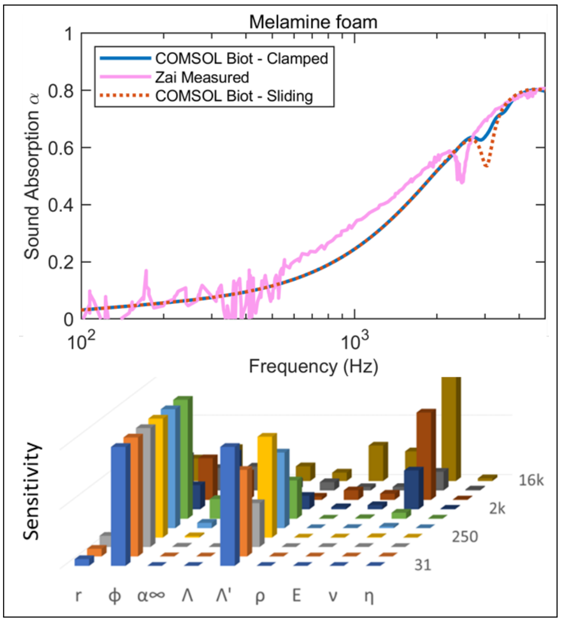

Figure 2. Results for melamine foam F1 simulations compared with experimental results [14] and sensitivity study for melamine foam F1.

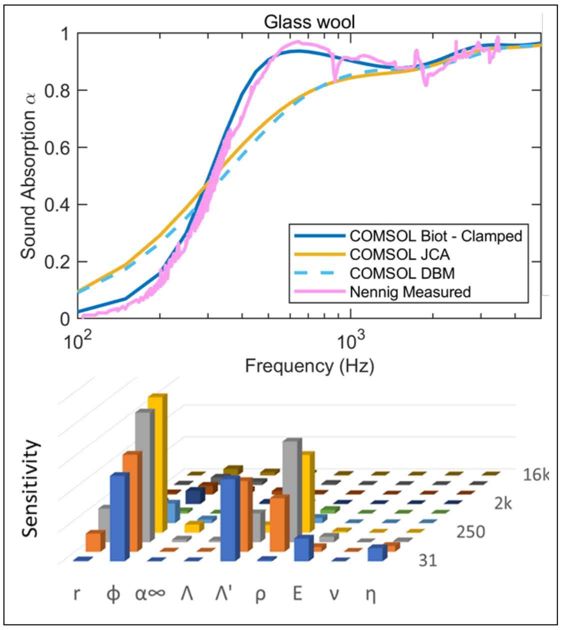

Figure 3. Results and sensitivity analysis for glass wool G3, Table 2, considering the DBM, JCA and Biot models and measured results [19].

from the same source and shows absorption coefficient measurements, and is thus used for the comparison. The results can be seen in Fig. 3. The results for the COMSOL Biot- Clamped match well with the measured absorption, similar to the result for the melamine foam. Again, there is a clear difference between the DBM and JCA models against the experimental results and the Biot model. The ML-Biot results exactly match the COMSOL Biot-Sliding results, as it should, but are not distinguishable in the plot due to the overlapping of the curves. Through the Biot model it is possible to get a good match with the experimental results, which cannot be achieved with models as DBM or JCA which do not take into account the structural phase. The sensitivity study indicates that porosity ϕ, thermal characteristic length Λ' and density ρ are the most important parameters in this scenario.

3.3 Stone wool

Table 2, bottom, shows the gathered data for stone wool. The results for sample S2 from [12] can be seen in Fig. 4. The source paper does not include measurements for absorption coefficient. However, they provide a calculation done with a modified Biot model; their results coincide almost exactly with the ML-Biot curve.

The calculations and the COMSOL Biot-Clamped model match considerably, although here the influence of the solid phase is seen as a peak, not a dip as in Fig 1. The COMSOL Biot-Clamped simulation seems to be more conservative with the height of the peak, this is related to the loss factor which is considered to be 0.3. This value seems high for a mineral wool – the loss factor should be for the solid phase alone, without the thermo-viscous effects, but there needs to be more measurements and information about this to confirm. The sensitivity study in this case indicates a big dependence on airflow resistivity and porosity. Even for a material as stone wool, which is considerably different to a melamine foam, the COMSOL Biot-Clamped model seems to perform well.

4. DISCUSSION AND CONCLUDING REMARKS

The DBM, JCA, and Biot models, using transmission line theory and finite element modeling tools, were fed data gathered from literature. These models were compared against each other for each type of material analysed: melamine foam, glass wool and stone wool. For the three types of materials, the results aligned well with the exper-

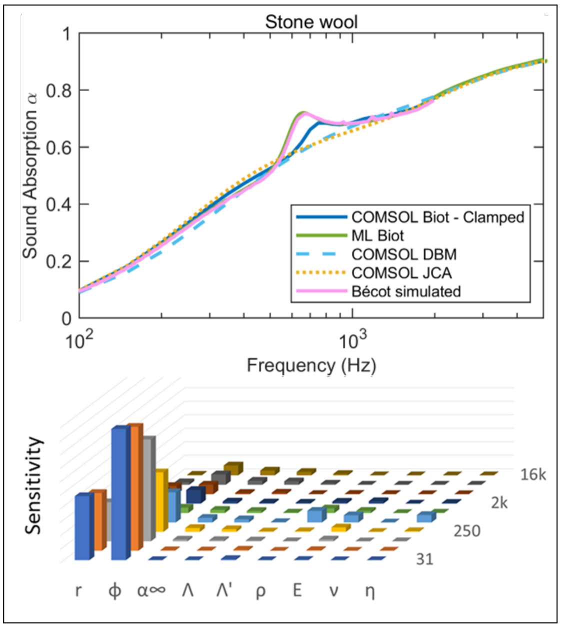

Figure 4. Results and sensitivity analysis for stone wool S2, Table 2, considering the DBM, JCA and Biot models and simulated results from [12].

imental reported results, but more simulations have to be done with other new sources of information to confirm if the data sources are reliable and if it is possible to mix data from diverse sources and still trust the results. The transmission line model matches with the corresponding models in FEM, such as ML-DBM and COMSOL-DBM, or ML-Biot, COMSOL- Biot Sliding and COMSOL- Biot Infinite. This match confirms that the conditions set in the FEM model are well established. The model COMSOL Biot - Clamped results differ from the other models' results because the boundary conditions affect the behavior of the resonance of the structural phase of the material, nevertheless it is a similar behavior and the dip or peak related to the resonance changes slightly. However, the COMSOL Biot - Clamped is the simulation with most similar conditions to measurements, and it agrees satisfactorily with the measured results. These resonance effects related to the structural phase can be seen in the three cases studied, but for some only in a limited frequency range. However, in some samples not reported, there was no visible structural phase behaviors in the Biot model and the measured results. At this stage it is difficult to state what combination of parameter values will show an influence on the dip or peak related to the solid phase. As mentioned in the introduction, the use of a more complete model can show these important effects of the structural phase. The sensitivity study showed the importance of the loss factor and its direct relation to the amplitude of the peaks/dips in the results. The selected plots shown in this paper are the ones which match closest to the measured results. For the other cases seen in Table 2 it was seen that if the parameter data was obtained from different sources, the results would not match as well. Finding literature sources where all the necessary material parameters were given was very difficult. The lack of information has become an obstacle for progressing in model updating and in the comprehension of porous materials as the ones presented in this work.

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