The Use of Mathematical Models in Determining Acoustic Absorption Coefficient of New Composite Porous Materials

Ancuţa Elena TIUC
Department of Environmental Engineering and Sustainable Development Entrepreneurship, Technical University of Cluj-Napoca, Romania, Cluj-Napoca, 103-105 Muncii Bd., Ancuta.TIUC@imadd.utcluj.ro

Ovidiu VASILE
Department of Mechanics, University Politehnica of Bucharest, Splaiul Independentei 313, 060042 Bucharest, Romania, ovidiu_vasile2002@yahoo.co.uk

Horaţiu VERMEŞAN
Department of Environmental Engineering and Sustainable Development Entrepreneurship, Technical University of Cluj-Napoca, Romania, Cluj-Napoca, 103-105 Muncii Bd., Horatiu.Vermesan@imadd.utcluj.ro

Ovidiu NEMEŞ
Department Environmental Engineering and Sustainable Development Entrepreneurship, Technical University of Cluj-Napoca, Romania, Cluj-Napoca, 103-105 Muncii Bd., Ovidiu.Nemes@imadd.utcluj.ro

Abstract: - The paper analyzes the possibility of determining the acoustic absorption coefficient by means of mathematical models from the literature for new composite porous materials. The materials studied were made of fir sawdust and flexible polyurethane foam with open pores. The acoustic absorption coefficient of the materials was determined experimentally by means of the impedance tube. The experimental results were compared with those obtained by modeling with the *Maple* 16 software, by inserting the material characteristics into the mathematical equations. The models used in this study were Delanz-Bayley adapted for foams, Allard-Champoux and Hamet-Berengeir. The results of this study show that the analyzed models are not suitable for new composite porous materials and that new models should be developed to correctly describe their acoustic absorption properties.

Keywords: - sound absorption coefficient, frequency, acoustic impedance, porosity, open-cell foams.

1. INTRODUCTION

Noise pollution is regarded among the most serious environmental issues due to rapid developments of modern industries and transportation [1,2]. A solution for reducing sound pollution is to develop new materials with high sound absorption efficiency [1-3].

Flexible polyurethane foams (FPFs) are used in thermal insulation and acoustic absorption [4, 5]. Sound absorption properties of FPFs can be improved by mixing with sawdust resulting new composite porous materials with open pores. These materials can absorb sound with high efficiency and can increase value of fir sawdust [6]. Porous materials are widely used as sound absorbing materials in noise control engineering [7]. They can be obtained by mixing various synthetic materials like sawdust, glass wool, minerals foams and fibers [7].

One of the key issues is to determine the relationships between the structural parameters and the sound absorption coefficient of these new composite materials [8]. For this, models for predicting the acoustic impedance characteristics and propagation constant of fibrous materials were studied. In the last few years many models were developed. Delany and Bazley [9], model is obtained by best-fitting a large amount of experimental data; it only requires the airflow resistivity input parameter, witch is easily measurable, for it is a simple empirical approach that is however a good and fast approximation to the solution. Dunn and Davern [10], uzed the same method to define empirical relations between characteristics impedance and propagation constant of porous foam materials and multilayer absorbers and they calculated new regression constants for polyurethane foams, using few samples with low airflow resistivity values. Hamet [11], model take into account both viscous and thermal dissipation. The model requires three parameters to characterize the material and it is well-suited for moderate porous materials. Qunli [12], proposed an empirical relation for acoustical impedance of foam materials using a large amount of experimental data with a wider range of flow resistivity. Attenborough and Buser [13], developed a rigid frame model to study the acoustical properties of light snow. This model was extended by Marco et al. [14] for higher densities. Another researcher, Miki [15], proposes an improved relationship based on Delany-Bazley model for a wider range frequency.

The microscopic model of sound propagation is more complicated. More sophisticated models which take into account structural will not be considered because they feature a large number of parameters which are not always available.

By analyzing national and international research, concerns have been identified about the possibility of using different types of waste in composite materials with different properties. In this paper we studied the possibility of obtaining the acoustic absorption coefficient using empirical models from the literature for the new composite porous materials based on waste.

The materials analyzed in this study were made of fir sawdust and flexible polyurethane foam with open pores. The acoustic absorption coefficient for the new composite materials was determined experimentally by the impedance tube method. The experimental data were compared to those obtained from the Maple 16 software, by inserting the material characteristics into the mathematical equations of the following models: Delanz-Bayley adapted for foams, Allard-Champoux and Hamet-Bérengeir.

2. MODELS FOR ACOUSTIC ABSORPTION

Acoustic properties of a porous sound absorbing material, i.e. the characteristic impedance Z_c and the propagation constant k_c, are as follows:

$$Zc = R + jX$$
$$k_c = \mathrm{A} + j\mathrm{B} \tag{1}$$

where R is the real component, X is the imaginary component, A is the attenuation constant and B is the phase constant.

Under well-defined pressure and temperature conditions, e.g. the air characteristic impedance, Z_o is:

$$Z_0 = \rho_0 \cdot c \tag{2}$$

where ρ_O is the density of air; c is the speed of sound in the air.

Knowing the characteristic impedance of the material (Z_c), calculated using mathematical models, the impedance can be determined on the surface (Z) of the material in a system as shown in Figure 1.

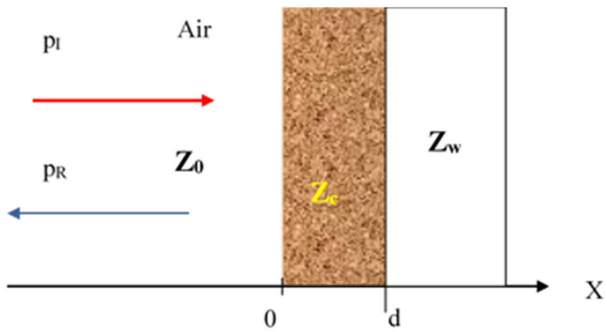

Figure 1. Surface impedance determination system

A material of (d) thickness and a characteristic Z_c impedance located on a Z_w impedance wall has a surface impedance (x = 0) given by the equation:

$$Z = Z_c \frac{Z_p \cosh(k \cdot d) + Z_c \sinh(k \cdot d)}{Z_p \sinh(k \cdot d) + Z_c \cosh(k \cdot d)} \tag{3}$$

In practice, the material of (d) thickness is placed on a wall where impedance is considered infinite, in which case we will have [16]:

$$Z = Z_c \cdot \coth(k_c \cdot d) \tag{4}$$

Thus, the acoustic absorption coefficient can be calculated as follows (r is the sound pressure reflection coefficient):

$$\alpha = 1 - |r|^2 = 1 - \left| \frac{Z - Z_0}{Z + Z_0} \right|^2 \tag{5}$$

2.1 Delany and Bazley model adapted for foams

Equations for characteristic impedance (Z_c) and propagation constant (k_c) of the material are [9]:

$$Z_c = Z_0 \left(1 + 0.2814 \left(\frac{f}{\sigma} \right)^{-0,3659} - 0.0974 \cdot j \left(\frac{f}{\sigma} \right)^{-0,6144} \right) \tag{6}$$

$$k_c = \frac{\omega}{c}\left(0.1682\left(\frac{f}{\sigma}\right)^{-0,5728} + j\left(1 + 0.2549\left(\frac{f}{\sigma}\right)^{-0,4657}\right)\right) \quad (7)$$

where Z_0 is the air characteristic impedance; f is the frequency; ω is the angular frequency; σ is the airflow resistivity; $j = \sqrt{-1}$; c is the speed of sound in the air.

This model is only applicable for the following condition:

$$10 \le \frac{f}{\sigma} \ge 1000 \quad (8)$$

2.2 Hamet and Bérengier model

Hamet and Bérengier designed a phenomenological model for porous pavements [17]. This model depends on three parameters of the studied material: porosity, airflow resistance and tortuosity. In addition to the three parameters in this model, the parameters that target the material-fluid interaction were introduced, respectively the viscous and thermal dependences. Thus, the equations for the characteristic impedance (Z_c) and the propagation constant (k_c) of the material become as follows [17]:

$$Z_c = Z_0\sqrt{\frac{\alpha_\infty}{\gamma}\cdot\frac{1}{\phi}}\cdot\sqrt{1 - j\frac{f_\mu}{f}}\frac{1}{\sqrt{1-\left(1-\frac{1}{\gamma}\right)\frac{1}{1-j\frac{f_\theta}{f}}}} \quad (9)$$

$$k_c = k_a\sqrt{\alpha_\infty\cdot\gamma}\cdot\sqrt{1 - j\frac{f_\mu}{f}}\cdot\sqrt{1-\left(1-\frac{1}{\gamma}\right)\frac{1}{1-j\frac{f_\theta}{f}}} \quad (10)$$

where ϕ is the porosity; α_∞ the tortuosity; γ the adiabatic constant; k_a is the air propagation constant; f_μ and f_θ are viscous and thermal dependences, respectively:

$$f_\theta = \frac{\sigma}{2\pi\cdot\rho_0\cdot N_{pr}} \quad (11)$$

$$f_\mu = \frac{\sigma\cdot\phi}{2\pi\cdot\rho_0\cdot\alpha_\infty} \quad (12)$$

where N_{pr} is the Prandtl's number.

2.3 Allard and Champoux model

Allard and Champoux [18] postulated a model that is based on the assumption that the thermal effects are dependent on frequency. The model describes a porous layer as a mixture of air and an elastic frame. This model aims to the prediction of two material parameters, i.e. the effective density ρ (kg/m^3) and the bulk modulus K (Kg/m·s).

$$\rho = 1.2 + \sqrt{-0.0364\left(\frac{\rho_0\cdot f}{\sigma}\right)^{-2} - j0.1144\left(\frac{\rho_0\cdot f}{\sigma}\right)^{-1}} \quad (13)$$

$$K = 101320\frac{j29.64 + \sqrt{2.82\left(\frac{\rho_0\cdot f}{\sigma}\right)^{-2} - j24.9\left(\frac{\rho_0\cdot f}{\sigma}\right)^{-1}}}{j21.17 + \sqrt{2.82\left(\frac{\rho_0\cdot f}{\sigma}\right)^{-2} - j24.9\left(\frac{\rho_0\cdot f}{\sigma}\right)^{-1}}} \quad (14)$$

The characteristic impedance (Z_c) and the propagation constant (k_c) of the material required to be able to calculate the acoustic absorption coefficient can be determined with the following equations:

$$Z_c = \sqrt{\rho\cdot K} \quad (15)$$

$$k_c = j\cdot 2\cdot\pi\cdot f\sqrt{\frac{\rho}{K}} \quad (16)$$

3. MATERIALS AND METHODS

Fir wood sawdust with a size greater than 2 mm, humidity of 10.1% and density of 0.033 g/cm^3 was used for making the composite materials with sound absorbing properties. As a binder, a flexible two-component polyurethane foam with open pores (Elastopor H 2400/5 system manufactured by BASF) was used.

Two types of materials sample were used for experimental validation. These two samples are named 100-FPF (100% Flexible Polyurethane Foam) and 50-FPF (50% Flexible Polyurethane Foam and 50% fir sawdust), see figure 2.

The sound absorption coefficients were determined by the impedance tube method. The material measurements were based on a two-microphone transfer-function method according to ISO 10534-2 [19].

Figure 2. Materials used for determining the sound absorption coefficient.

A medium Brüel&Kjaer Type 4206 A tube kit was used to measure various acoustic parameters for a frequency range of 100 ÷ 3200 Hz.

The medium impedance tube kit consisted of a 63.5 mm diameter tube and therefore materials were cut in round samples with a 63.5 mm diameter. Acoustic signal generated by the PULSE Analyzer 3560-B-030 was amplified by the 2716 B&K Power amplifier and the results were recorded and processed on a PC.

4. RESULTS AND DISCUSSIONS

Flow resistivity of materials was estimated from empirical Eq. (17); the measurement of Z_{Re} was performed by determining the surface impedance of two samples backed with a rigid wall, in relation with the material characteristic impedance [20] as follows:

$$\sigma_0 = \left[(Z_{\mathrm{Re}} - \rho_0 \cdot c)/0.051\rho_0 \cdot c \cdot f^{-0.75}\right]^{1/0.75} \qquad (17)$$

The results obtained running the software (Maple 16), using the following analytical models: Delanz-Bayley adapted for foams, Allard-Champoux and Hamet-Bérengeir were plotted and validated with the experimental results. Figures 3 and 4 show the variation of the acoustic absorption coefficient with frequency for the two analyzed materials.

Figure 3 shows the variation with frequency of acoustic absorption coefficient for the open-pores polyurethane foam (100-FPF). The figure shows the values of the acoustic absorption coefficient measured at normal incidence and the values calculated using the Delany-Bazley foam model [9], the Allard-Champoux model [18] and the Hamet-Bérengeir model [17].

For a 100-FPF material, it is seen that the predicted (with Delanz-Bayley adapted for foams and Hamet-Berengeir models) and measured values are fairly similar in the frequency range of 100-1700 Hz. This phenomenon is typical for the Delany–Bazley model as reported elsewhere showing that the model is inadequate for very low and very high frequencies [21].

The Delany–Bazley and Hamet-Berengeir methods are a good approximation for overall broadband trend of acoustic behavior for flexible polyurethane foam.

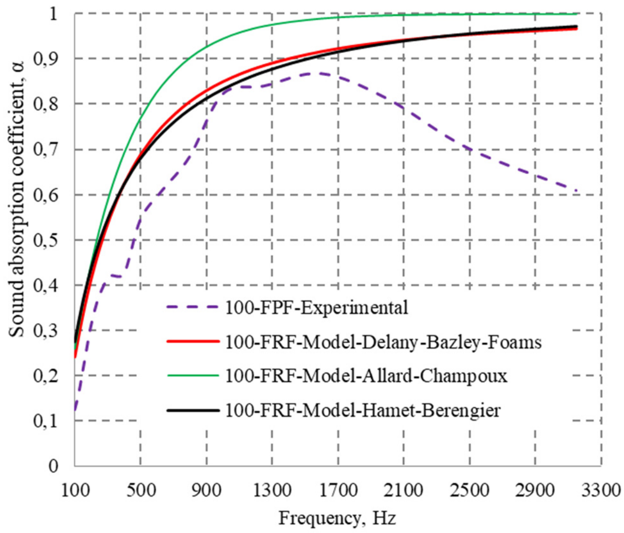

Figure 3. Sound absorption coefficient of 100-FPF sample (100% Flexible Polyurethane Foam)

Figure 4 shows the 50-FPF composite material acoustic absorption coefficient variation with frequency, measured at normal incidence and calculated using the three analytical models.

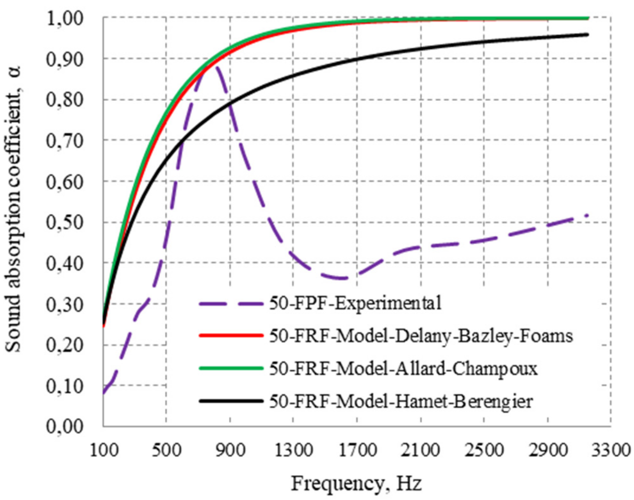

Figure 4. Sound absorption coefficient of 50-FPF (50% Flexible Polyurethane Foam and 50% fir sawdust)

The peak of absorption coefficient moved to lower frequencies for the composite materials. Two reasons may be described regarding this behavior as addressed by Wassilieff [22] for wood-based fibers and shavings. Firstly, the composite materials have a higher moist content than the polyurethane foams samples, causing the absorption coefficient to decrease. Secondly, sawdust stiffens the material skeleton which increases structural damping and moves resonances to lower frequencies.

Figure 4 shows the Delany–Bazley and Allard-Champoux models as applied to the composite materials. It can be seen that the model is in agreement with experimental data at least for frequencies below 700 Hz. However, for higher frequencies, the Delany–Bazley model is unable to model sound absorption behavior of composite materials.

5. CONCLUSIONS

Comparing experimental data with plots obtaining by running various mathematical models shown that for the 100-FPF material, the predicted (with Delanz-Bayley adapted for foams and Hamet-Berengeir models) and measured values of acoustic absorption coefficient are fairly similar in the frequency range of 100-1700 Hz

For the 50-FPF composite material Delany–Bazley and Allard-Champoux models is in agreement with experimental data for frequencies below 700 Hz.

The models were not accurate at high frequencies for the new composite materials. However, for some configurations shown herein the difference between the measured and predicted values is relatively small. It is difficult to use this empirical approach, as the optimum flow resistivity has to be obtained experimentally.

The overall results of this study show that composite porous materials have a very complex behavior in absorption of sound waves. For these more complex models are needed for understanding this behavior. In order to obtain a more suitable model for composite materials, it is necessary to achieve a higher number of experimental measurements of both the mathematical parameters and the acoustic characteristics in order to subsequently identify the optimal coefficients in the mathematical equations.

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REFERENCES

[1] Rădoi A. M., Enescu N., Magheți I., Determination of the Noise Level Produced by Road Traffic, Journal of Acoustics and Vibratio, vol XIII, issue 2, 2016, pp.63-67.

[2] Gwon J.G., Kim S.K., Kim J.H., Sound absorption behavior of flexible polyurethane foams with distinct cellular structures, Materials & Design, 89, 2016.

[3] Wang Y., Zhang C., Ren L., Ichchou M., Galland M.A., Bareille O., Influences of rice hull in polyurethane foam on its sound absorption characteristics, Polymer Composites, 34, 2013.

[4] Arenas J.P., Crocker M.J., Recent trends in porous sound-absorbing materials, Sound and Vibration, 44, 2010.

[5] Defonseka C., Practical Guide to Flexible Polyurethane Foams, Smithers Rapra, 2013.

[6] Tiuc A.E., Moga L., Improvement of Acoustic and Thermal Comfort by Turning Waste into Composite Materials, Romanian Journal of Acoustics and Vibration, 10, 2, 2013.

[7] Soto G., Castro A., Vechiatti N., Iasi F., Armas A., Marcovich N.E., Mosiewicki M.A., Biobased porous acoustical absorbers made from polyurethane and waste tire particles, Polymer Testing, 57, 2017.

[8] Mirowska M., Czysewski K., Influence of thickness and structural parameters on sound absorption coefficients of porous materials, International Congress on Acoustics, Madrid, 2-7 September, 2007.

[9] Delany M.E., Bazley E.N., Acoustical properties of fibrous absorbent materials, Applied Acoustics, 3, 1970.

[10] Dunn I.P., Davern W.A., Calculation of acoustic impedance of multi-layer absorbers, Applied Acoustics, 19, 1986, pp.321–334.

[11] Hamet J.F., Modélisation Acoustique dun enrobé Drainant, Bron: Rapport INRETS, 1992, pp. 159.

[12] Qunli W., Empirical relations between acoustical properties and flow resistivity of porous plastic open-cell foam, Applied Acoustics, 25, 1988, pp.141–148.

[13] Attenborough K., Buser O., On the application of rigid-porous models to impedance data for snow, Journal of Sound and Vibration, 124, 1988, pp.315–327.

[14] Marco O., Buser O., Villemain P., Analysis of a rigid frame model of porous media for the acoustic properties of dense snow, Journal of Sound and Vibration, 196, 4, 1996, pp.439–451.

[15] Miki Y., Acoustical properties of porous materials, Modifications of Delany-Bazley models. Journal of Acoustical Society of Japan, 11, 1990, 19-24.

[16] Dutilleux G., Ecotiere D., Automatic characterisation of ground surfaces from in situ measurements, Acoustics, Paris, 2008.

[17] Hamet J.F., Berengier M., Acoustical characteristics of porous pavements: a new phenomenological model. In Proc. Inter-noise, pages 641–646, Leuven, Belgique, August 1993.

[18] Champoux Y., Allard J., Dynamic tortuosity and bulk modulus in air-saturated porous media, Journal of Applied Physics, 70, 1991, pp.1975–1979.

[19] Standard SR EN ISO 10534-2, Determination of sound absorption coefficient and acoustic impedance with the interferometer. Part 2. Transfer function method, 2002.

[20] Picard M.A., Solana P., Urchueguia J.F., A method of measuring the dynamic flow resistance and the acoustic measurement of the effective static flow resistance in stratified rockwool samples, Journal of Sound and Vibration, 216, 3, 1998, pp.495–505.

[21] Egab L., Wang X., Fard M., Acoustical characterisation of porous sound absorbing materials: a review, International Journal of Vehicle Noise and Vibration, 10, 2014, pp.129–149.

[22] Wassilieff C., Sound absorption of wood-based materials, Applied Acoustics, 48, 4, 1996, pp.339–356.