Prediction of Acoustic Properties of Porous Building Materials

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This article presents an empirical model for predicting acoustic properties of a composite material which is a mixture of sand and polyurethane resin as the binder. The parameters of the model were determined based on the experimental testing of samples with the thickness from 10mm to 50mm. Measurements of the sound absorption coefficient were performed in the impedance tube using the transfer function method (SRPS EN ISO 10534-2: 2008). The same samples were used for measurement of the air flow resistance in order to form an empirical model. The measurements were made according to the method defined by SRPS ISO 9053:1994. It was concluded that the proposed model can be used in order to predict the absorption properties of sand as well as of other building materials whose grain structure is air permeable.

Keywords: Empirical model, Sound absorption, Sand, Material structure

1. INTRODUCTION

Today, noise has become a serious problem. In order to reduce its negative impacts in the form of hearing loss or a sleep disorder, people are looking for better acoustic solutions that will improve their living conditions. A lot of research is based on the development of materials that are suitable for sound absorption and noise reduction. Therefore, there is an increasing demand for materials with a high coefficient of sound absorption. As noise is a growing problem in the world, the research in the sound absorption of materials gains importance. Sound-absorbing materials are used to improve indoor acoustic comfort, and in recent years their application in the open has been increased in the form of absorption barriers. Among other things, protection against noise is one of the segments where natural materials, such as granular and fibrous, has a prominent place. Therefore, these materials are the subject of numerous studies.

Composite materials are increasingly used for sound insulation. Particularly important are the so-called organic compositions, such as rubber, plastics and the materials that represent a waste of industrial processes. Zainulabidin et al. [1] studied the acoustic properties of two materials: rubber sponges and fiber glass wool.

The prediction of acoustic properties of materials from recycled rubber and polyurethane resin was performed using the model Allard & Champoux [2]. New innovative sound absorbers based on organic materials have great potentialc in the future because they are cheaper compared to other available materials [3].

Soleimani [4] and others examined the acoustic properties of a mixture of wood fibers and recycled plastics. Our results show that the addition of nano-clays in composite resin decreases water absorption and that plastics have a negligible water uptake. Perna [5] and others studied the absorption coefficient of materials which results from the mixing of sand and geopolymers. Geopolymers were used as a substitute for epoxy resin.

Mahzan S. et al. [6] investigated combinations of materials in which coconut is used as the main raw material and recycled rubber as a raw material with the use of polyurethane as the binder. Tests have shown that the absorption of this mixture is suitable for medium and high frequencies. The samples with 25% recycled rubber gave absorbance values greater than those that had 35% recycled rubber.

Semiha Yilmazer and Mesut B. Ozdeniz [7] analyzed the effect of moisture content on the acoustic properties of panels made of expanded perlite. The best results in terms of sound absorption in a moist environment were produced by silicate coated perlite.

Perna Ivana et al. [8] tests were performed based on the determination of the absorption coefficient of the material formed as a mixture of sand and geopolymers. The results showed that geopolymer-sand mixtures have good absorption properties and can be used as a substitute for epoxy resin. The mixing of two different fractions of sand results in a higher absorption coefficient. Another result of improving the sound absorption of this type of material is the possibility of its installation between other types of composite materials.

2. MATERIAL

By their nature, materials can be classified into two main groups: natural and artificial. Natural materials are those that can be installed in buildings without processing, such as wood, stone, sand, gravel, grain, materials of vegetable origin, while artificial materials, e.g. cement, gypsum, bricks or concrete are not found in nature - they are obtained through special technological procedures. Sand is a natural granular material. It is obtained by natural crushing and disintegration of rocks, where the level of fragmentation of the rock material is quite large. Sand can be described as an unconsolidated sediment with the size of grains of up to 4mm. In order to trace the grain size distribution, two methods are used: the method of sieving and the sedimentation method. With regard to the grain size of aggregates used in construction, the grain size distribution of these materials is most commonly defined by the sieving method [9].

Therefore, both of these experimental studies performed on circular patterns were made of sifted sand

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and a binder. The structure of the sample was formed by using granules of sand, gravel, and 10% of polyurethane resin as the binder. The binder has the same percentage share in all samples. The maximum size of granules was determined by the size of the mesh openings of 3mm. The samples were poured into moulds with the diameter of 100mm and a thickness of 10mm, 20mm, 30mm, 40mm and 50mm.

Figure 1: A sample of the mixture of sand and polyurethane resin

3. METHODS

The measurement of absorption was carried out in an impedance tube, by applying the transfer function method between two microphones, described by the standard EN ISO 10534-2 [10]. This method is based on the decomposition of a standing wave formed in the tube, by recording signals from the two microphones and calculating their transfer function. The reflection coefficient is calculated from the transfer function, and then the absorption coefficient is found in the conditions of normal incidence.

$$\alpha = 1 - \left|R\right|^2 \tag{1}$$

where: R is the reflection coefficient which is calculated according to the expression:

$$R = \frac{H - e^{-jks}}{e^{jks} - H} e^{j2k(l+s)} \tag{2}$$

where: H – the corrected transfer function, s – the distance between the microphones, l – the distance of the microphone which is closer to the sample, k – the wave number.

The method with a constant air flow was used for measuring airflow resistance, according to the standard ISO 9053:1991 [11]. The practical realization of the system for measuring airflow resistance is presented in paper [12]. The measuring cell has the form of a circular cylinder; it is made of plexiglass so that placing of the sample could be visually monitored. The inner diameter of the measuring cell is 100 mm. The vacuum pump ZAMBELLI, type ZB1 is used as a device for creation of airflow. The airflow is measured by means of a ball rotametre. The measuring range of the rotametre is 2÷30 l/min. A differential pressure meter TESTO 512 is used for measuring the pressure drop through the sample. This gauge has a measuring range of 0-200 Pa with the resolution of 0.1 Pa. The error of the measurement equipment is smaller than required by the standard [11].

Figure 2: A view of the realized measurement system for determination of airflow resistance

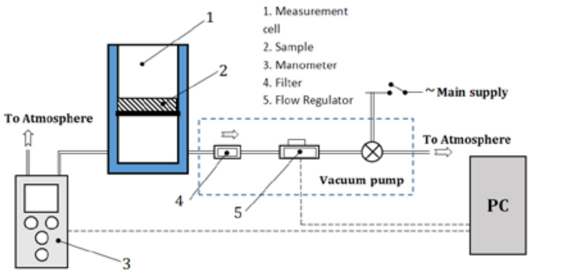

Figure 3: Block diagram of the steady-state airflow system

4. PROPOSAL OF A NEW EMPIRICAL MODEL FOR DETERMINATION OF ACOUSTIC PROPERTIES OF GRAIN MATERIALS

Theoretical models require five input parameters, which cannot often be simply and reliably determined. This is the main weakness of the so-called phenomenological or micro models for determination of acoustic properties of porous materials. Therefore, an experimental macro model for prediction of acoustic properties of composite materials made of sand, gravel and polyurethane resin is developed in this paper. The main advantage of such models is in their having one input parameter – longitudinal airflow resistance.

Sound propagation in an isotropic homogeneous material can be represented by the characteristic impedance (Zc) and the constant of sound propagation in the absorption material.

$$Z_c = R + jX \tag{3}$$

$$\gamma = \alpha + j\beta \tag{4}$$

Starting from the well-known Delany & Bazley relations:

$$R = \rho_0 c_0 \left[1 + C_1 \left(\frac{\rho_0 f}{r}\right)^{-C_2}\right] \tag{5}$$

$$X = -\rho_0 c_0 \left[C_3 \left(\frac{\rho_0 f}{r}\right)^{-C_4}\right] \tag{6}$$

$$\alpha = \left(\frac{2\pi f}{c_0}\right)\left[C_5 \left(\frac{\rho_0 f}{r}\right)^{-C_6}\right] \tag{7}$$

$$\beta = \left(\frac{2\pi f}{c_0}\right)\left[1 + C_7\left(\frac{\rho_0 f}{r}\right)^{-C_8}\right] \qquad (8)$$

where R and X are the real and imaginary parts of the characteristic acoustic impedance Z_c, and α and β the real and imaginary parts of the constant of propagation (γ) of sound in the absorption material, ρ_0 – the air density, f – the frequency, and r – the longitudinal airflow resistance.

Starting from the equations (9) through (13) and the recommendations of the European standard EN 12354-6:2003, the diffusion coefficient of sound absorption of porous materials can be calculated. For a diffuse acoustic field, the absorption coefficientmože α_s can be defined as:

$$\alpha_s = \int_0^{\pi/2} \alpha_\varphi \sin 2\varphi d\varphi \qquad (9)$$

$$\alpha_\varphi = 1 - \left|r_\varphi\right|^2 \qquad (10)$$

$$r_\varphi = \frac{Z' cos\varphi - 1}{Z' cos\varphi - 1} \qquad (11)$$

$$Z_c' = \frac{Z_c}{\rho_0 c_0} \qquad (12)$$

$$Z' = Z_c' \coth \gamma d \qquad (13)$$

where:

φ - the angle of incidence, in radians,

α_φ - the absorption coefficient for the plane sound wave, related to the angle φ,

r_φ - the reflection coefficient for the plane sound wave, related to the angle φ,

Z' - the normalized surface impedance of the layer

Z_c' - the normalized characteristic impedance of the absorption material,

d - the layer thickness, in metars.

The empirical macroscopic model for determination of acoustic properties of composites made of sand, gravel and polyurethane resin are rarely available in the scientific literature. The new model for prediction of acoustic properties of the mentioned composite was developed by applying the method of least squares. The calculation of coefficients C1, ..., C8, was done in such a way that the deviations of the absorption coefficient should be minimum in relation to the values obtained by the mesurements in the impedance tube.

The accuracy of prediction of the absorption coefficient was evaluated on the basis of the value of absolute and relative errors in relation to the measurement values in the impedance tube. The comparative analysis showed that new models for determination of the absorption coefficient give the values of absolute and relative errord within the allowed limits, defined for this type of empirical models.

Table 1: Empirical model for determination of acoustic properties of sand

Material	Sand
Longitudinal airflow resistance, r [Pas/m^2]	72032
Characteristic impedance, Z_c	$Z_c = \rho_0 c_0 \left[\left(1 + 0.010 \cdot C^{1.107}\right) - i\left(0.492 \cdot C^{0.700}\right)\right]$
Propagation coefficient, γ	$\gamma = \frac{2\pi f}{c_0}\left[\left(0.840 \cdot C^{0.007}\right) + i\left(1 + 0.477 \cdot C^{1.030}\right)\right]$
Absorption coefficient EN123546:2003	$\alpha_s = \int_0^{\pi/2} \alpha_\varphi \sin 2\varphi d\varphi$
Mean absolute error, $\Delta\overline{\alpha}$	0.0383
Mean relative error, $\overline{\varepsilon}$ [%]	30.69

5. MEASUREMENT RESULTS

The measurement results for the absorption coefficient of different patterns of sand on the diagram.

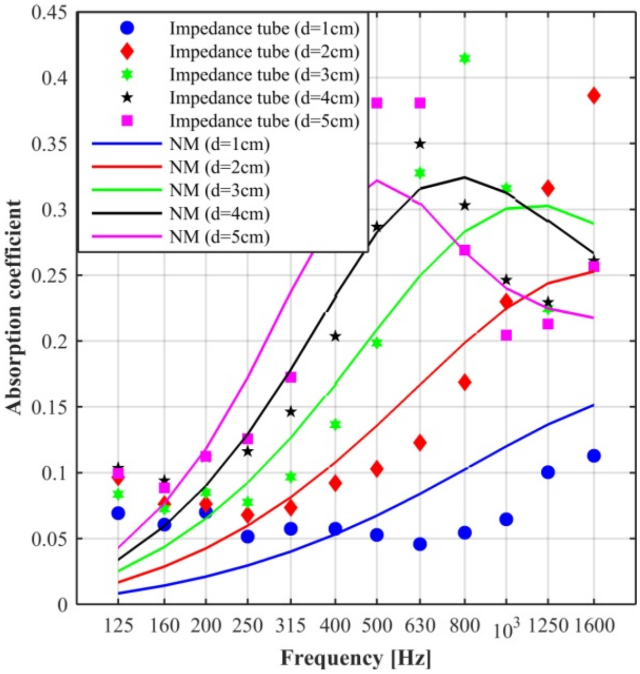

Figure 4: Empirical and experimental values of the absorption coefficient of sand

The following can be concluded for sand:

- the absorption coefficient of sand has considerably lower values than the absorption coefficient of recycled rubber and recycled plastics within the whole frequency range,
- the absorption coefficient of sand also increases with the increase in frequency up to a certain value, and then it decreases and has a maximum at considerably lower frequencies in relation to rubber and plastics,
- the material thickness also influences the increase of the absorption coefficient, but it behaves differently at low and high frequencies. At higher frequencies, over 1000 Hz, there is no point in using materials thicker than 20 mm because they

cause an opposite effect, i.e. they decrease the absorption coefficient. At lower frequencies, e.g. about 400 Hz, the effect of absorption coefficient is evident up to the thickness of 45 mm,

- in comparison with recycled rubber and plastics, sand has considerably worse absorption properties at the frequencies above 630 Hz, but it has considerably better properties at the frequencies from 400 to 630 Hz.

The deviation of the absorption coefficient obtained by the application of the newly proposed model in relation to the measurements in the impedance tube is 3.83%, [13] which is very good in comparison with the most frequently used limit value of 10% from the available scientific literature. The mean relative error has a slightly higher value of 35%, but it is primarily the consequence of deviations at greater thicknesses of samples and higher frequencies.

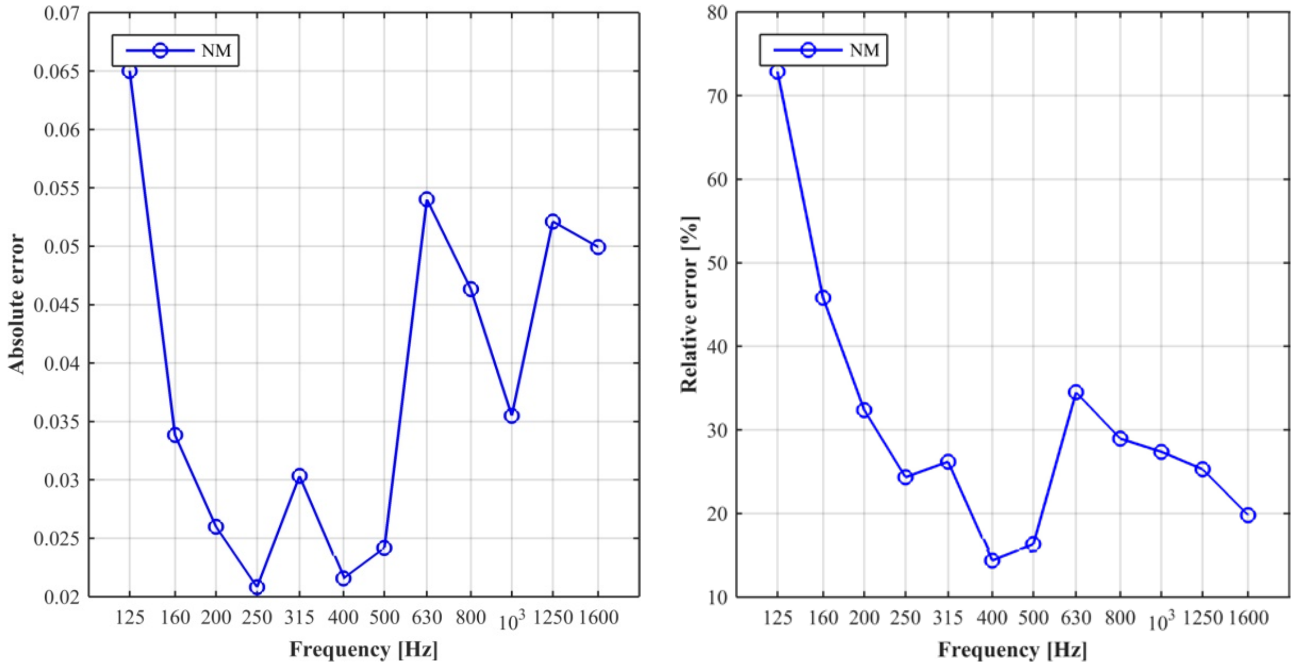

Figure 5: Absolute and relative error model

6. CONCLUSION

This paper presents the methodology of forming a macroscopic empirical model to predict acoustic properties of composite sand and polyurethane resins. The measured longitudinal airflow resistance for five different sample thicknesses was used as an input parameter for the model. The new model was confirmed by good absorption properties of composites in relation to recycled rubber and recycled plastic. The mean absolute error of the new model is 3.83% compared to the measured values of sound absorption coefficient in the impedance tube. Based on this, the new model can be considered to be a good estimate of the acoustic properties of sand with the maximum grit size of up to 3 mm, applying a binding agent of polyurethane resin. With the increasing number of materials that can be applied to the new model, one can expect its improvement in terms of predicting acoustic properties. Given that the analyzed material has a granular structure, it is realistic to expect that this model can be applied to predict the acoustic properties of other porous materials with a granular structure.

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