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THEORETICAL APPROACH TO DETERMINATION OF ACOUSTIC PROPERTIES OF BUILDING MATERIALS

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The presence of high level of acoustic load especially in urban areas is becoming a serious problem in the present. In order to protect people against adverse effects of audio noise on health and personal well-being in buildings located in such areas, convenient construction materials with sophisticated geometric arrangement should be used. Bearing structures of new houses in the Czech Republic are widely made of different types of brick blocks. Such brick blocks consist of solid matrix and cavities designed in an optimized geometrical way in order to assure better thermal and hygric properties. Previous studies dealing both with acoustic properties in an empirical way and with the theoretical aspects of acoustic attenuation in building materials were not very numerous. Nevertheless, they gain constantly in importance with increasing acoustic load of the buildings surroundings. In this paper, a theoretical approach for the determination of acoustic properties, which is convenient for the description of sound waves propagation in building materials, is introduced.

Keywords: Acoustic attenuation, Lossy media, Brick block, Heterogeneous material, Homogenization.

1 INTRODUCTION

High level of acoustic load is one of discomforting aspects that negatively influences life in urban areas. Especially places close to main thoroughfares or airports are significantly affected by the presence of noise caused by heavy traffic load. High level of noise acts negatively on the human well-being which was proved in recent publications relating road traffic noise to health problems such as cardiovascular diseases (Babisch 2014) or diabetes (Sorensen *et al.* 2013). Appropriate urban planning is the key factor that leads to reduction of noise level in living areas. Gozalo *et al.* (2013) analyzed urban noise by means of continuous equivalent sound level in 27 cities in Spain, Chile and Portugal in order to prove that such analysis can be used as a tool for urban planning and for designing sound pollution prevention policies. Similar research was conducted by Gozalo *et al.* (2015) in 21 locations in Madrid. Besides convenient urban planning policies, attention has also to be paid to convenient design of building envelopes and selection of building materials with good acoustical performance represented by high acoustic attenuation coefficient. It should be noted that, besides high acoustic attenuation, such materials are also supposed to be good thermal insulators.

In the Czech Republic, brick is a traditional material used for construction of bearing walls of family houses. In order to meet demands on low thermal conductivity, bricks with artificially created cavities of designed geometry, so called brick blocks, are widely used for building constructions. Due to the fact, that geometry of cavities crucially affects acoustic properties, development of new acoustically optimized brick blocks has to be accompanied by measurements of acoustic attenuation in audible frequency spectra and modeling of sound wave propagation in lossy media.

In this paper, a theoretical approach for determination of acoustic properties of brick block is introduced.

2 ACOUSTIC ATTENUATION MODEL

Acoustic attenuation is the main parameter used for description of the energy loss at the sound propagation in materials. It is mainly caused by viscosity of the material that converts sound energy into heat energy and for heterogeneous media also by scattering. Experimental measurements show that the acoustic attenuation coefficient of a wide range of viscoelastic materials such as polymers, soft tissues and porous materials can be expressed by the following power law formula

$$P(x+\Delta x) = P(x)e^{-\alpha(\omega)\Delta x} \tag{1}$$

where P [Pa] is the acoustic pressure, Δx [m] is the wave propagation distance, ω [s^{-1}] is the angular frequency and $\alpha(\omega)$ [m^{-1}] is the attenuation coefficient that can be described as

$$\alpha(\omega) = \alpha_0 \omega^{\eta} \tag{2}$$

where α_0 [s m^{-1}] and η [-] are real non-negative material parameters obtained by fitting experimental data. η ranges from zero to two and is approximately equal to one for soil and rocks, two for many metals and crystalline materials and between one and two for soft tissues. Angular frequency defined by Eq. 3 is dependent on the frequency f [Hz] which is in the case of audible audio spectrum in a range of 20 Hz – 20 kHz.

$$\omega = 2\pi f \tag{3}$$

A generally accepted model widely used for calculation of frequency dependent acoustic attenuation was formulated by Szabó (Szabó 1994). It is based on time convolution integral dissipative acoustic wave equations and is defined as

$$\Delta p = \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} + \frac{2\alpha_0}{c_0} S_\eta(p) \tag{4}$$

and

$$S_\eta(p) = \begin{cases} \partial p / \partial t, & \eta = 0 \\ -\dfrac{2\Gamma(\eta+2)\cos[(\eta+1)\pi/2]}{\pi}\displaystyle\int_0^t \frac{p(\tau)}{(t-\tau)^{\eta+2}}\,d\tau, & 0 < \eta < 2 \\ -\partial^3 p / \partial t^3, & \eta = 2 \end{cases} \tag{5}$$

where p [Pa] is the acoustic pressure, Γ is gamma function and c_0 [m s^{-1}] is the speed of sound.

3 ACOUSTIC MODEL OF THE BRICK BLOCK

3.1 Studied Material

In this paper, brick block Heluz Family 50 with dimensions 247 x 500 x 249 mm manufactured by Czech company Heluz Brick Industry was studied. It was designed with a primary aim to achieve good thermal properties (low thermal conductivity), which is ensured, by a high amount of air. In dry state, the brick body consists of two phases, the solid phase represented by the ceramic matrix and the gaseous phase represented by pores. The amount of air in the brick body f_{pores} is intentionally high; the total open porosity is equal to 0.51. Air cavities with the shape presented in Figure 1 significantly contribute to the increase of the total amount of air and further improve thermal properties. The volumetric fraction of air in the cavities $f_{cavities}$ is 0.56 and the volumetric fraction of the brick body f_{body} is 0.44.

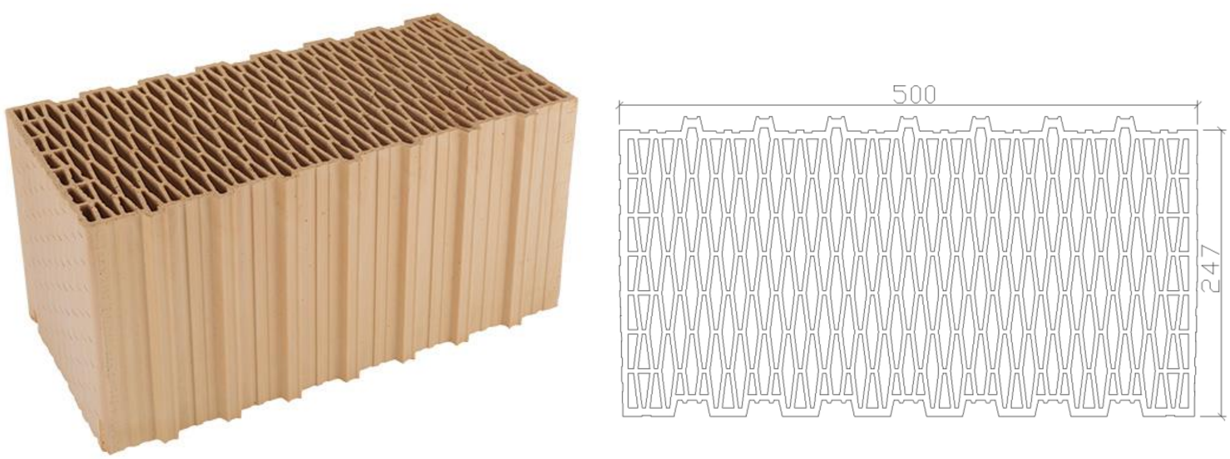

Figure 1. Brick block Heluz Family 50.

3.2 Homogenization procedure

Homogenization principles are frequently used for estimation of various parameters of heterogeneous materials. Their application is most common in the stress-strain analysis or in the estimation of the thermal conductivity (Pavlík *et al.* 2013), permittivity or electrical conductivity of two- or three-phase materials. The model proposed by Szabó (Szabó 1994), which will be used in this paper, was derived for homogeneous materials. However, dry brick block is a typical heterogeneous, two-phase material. Therefore, Szabo's model utilization for calculations has to be accompanied by an estimation of effective input parameters using homogenization principles.

Homogenization techniques are based on determination of an effective value of observed material's property. Input parameters for such calculations are volumetric fraction and property of each involved phase. Concerning the studied brick block, the volumetric fraction of air consists of that present in pores f_{pores} which is in the case of dry brick block equal to the total open porosity, i.e., 0.51. Taking the total brick volume as a reference, one obtains f_{pores} = 0.2244. Adding $f_{cavities}$ to f_{pores}, the total volumetric fraction of air f_{air} is equal to 0.7844. The volumetric fraction of solid matrix f_{matrix} is equal to $1 - f_{air}$ = 0.2156.

In this paper, two parameters, the sound velocity $c_{0,eff}$ and $\alpha_{0,eff}$, as an input parameter to the model proposed by Szabó was estimated by three widely used homogenization formulas.

Wiener's bounds, according to the Wiener's original work (Wiener 1912) represents the upper limit (Eq. 6) and the lower limit (Eq. 7) of the effective sound velocity,

$$c_{0,eff} = f_{air} c_{0,air} + f_{matrix} c_{0,matrix} \tag{6}$$

$$c_{0,eff} = \frac{1}{\dfrac{f_{air}}{c_{0,air}} + \dfrac{f_{matrix}}{c_{0,matrix}}} \tag{7}$$

where $c_{0,air}$ [m s^{-1}] is the sound velocity in air equal to 343.4 m s^{-1} at 20 °C (Haynes 2016) and $c_{0,matrix}$ [m s^{-1}] is the sound velocity in ceramic matrix equal to 3650 m s^{-1} at 20 °C (Lide 1991). Lichtenecker's model (Lichtenecker 1926) for a two-phase system is defined as

$$c_{0,eff} = \sqrt[k]{f_{air} c_{0,air}^{k} + f_{matrix} c_{0,matrix}^{k}} \tag{8}$$

where k [-] is a parameter varying within the [−1, 1] range. Thus, the extreme values of k correspond to the Wiener's boundary values. The parameter k may be considered as describing a transition from the anisotropy at $k = -1$ to another anisotropy at $k = 1$. Lichtenecker's formula for $k = 0$ is expressed as

$$c_{0,eff} = e^{f_{air} \ln(c_{0,air}) + f_{matrix} \ln(c_{0,matrix})} \tag{9}$$

$\alpha_{0,eff}$ was calculated in the same way as $c_{0,eff}$. Attenuation coefficient of air $\alpha_{0,air}$ is very low and can be considered as equal to zero ($1 \cdot 10^{-12}$ s m^{-1}). Attenuation coefficient of ceramic matrix $\alpha_{0,matrix}$ was determined from the data measured by Abdullah and Sichani (2009) for concrete with similar properties to brick body. $\alpha(\omega)$ measured for the frequency f = 19.736 kHz is equal to 1.663 m^{-1}. Substituting Eq. 3 to Eq. 2 and parameter $\eta = 1$ for solid rocks, $\alpha_{0,matrix}$ was calculated. It is equal to $1.34 \cdot 10^{-5}$ s m^{-1}.

4 RESULTS AND DISCUSSION

The effective sound velocity of brick block calculated by means of Wiener's bounds and Lichtenecker's model with different empirical coefficients k is presented in Table 1.

Table 1. Effective sound velocity $c_{0,eff}$ of brick block Heluz Family 50.

Model	$c_{0,eff}$
Wiener's upper bound	1056.3
Wiener's lower bound	426.7
Lichtenecker's model k = 0.1	600.5
Lichtenecker's model k = 0.2	633.5
Lichtenecker's model k = 0.3	684.4
Lichtenecker's model k = 0.4	712.9
Lichtenecker's model k = 0.5	759.6
Lichtenecker's model k = 0.6	811.0
Lichtenecker's model k = 0.7	866.9
Lichtenecker's model k = 0	571.6

The lowest effective sound velocity value calculated by Wiener's parallel model and the highest one calculated by Wiener's serial model is equal to 426.7 m s^{-1} and 1056.3 m s^{-1}, respectively. The effective sound velocity calculated by all the presented models is closer to the velocity of sound in air (343.4 m s^{-1} at 20 °C) due to high volumetric fraction of air (f_{air} = 0.7844).

The effective attenuation coefficient of brick block calculated by means of Wiener's bounds and Lichtenecker's model with different empirical coefficients k is presented in Table 2. The lowest effective attenuation coefficient value calculated by Wiener's parallel model and the highest one calculated by Wiener's serial model is equal to $1.27 \cdot 10^{-12}$ s m^{-1} and $2.89 \cdot 10^{-6}$ s m^{-1}, respectively.

Table 2. Effective attenuation coefficient $\alpha_{0,eff}$ of brick block Heluz Family 50.

Model	$\alpha_{0,eff}$
Wiener's upper bound	$2.89 \cdot 10^{-6}$
Wiener's lower bound	$1.27 \cdot 10^{-12}$
Lichtenecker's model k = 0.1	$6.04 \cdot 10^{-10}$
Lichtenecker's model k = 0.2	$1.18 \cdot 10^{-8}$
Lichtenecker's model k = 0.3	$1.41 \cdot 10^{-7}$
Lichtenecker's model k = 0.4	$2.93 \cdot 10^{-7}$
Lichtenecker's model k = 0.5	$6.25 \cdot 10^{-7}$
Lichtenecker's model k = 0.6	$1.04 \cdot 10^{-6}$
Lichtenecker's model k = 0.7	$1.50 \cdot 10^{-6}$
Lichtenecker's model k = 0	$3.44 \cdot 10^{-11}$

5 CONCLUSIONS

In this paper, Szabó's acoustic model valid for homogeneous materials was applied for brick block Heluz Family 50, which, due to complex geometry of incorporated cavities, exhibits very good thermal properties. In order to use this model properly for simulation of sound waves propagation in heterogeneous building materials, such as the analyzed brick block is, it was necessary to calculate the effective input parameters by means of appropriate homogenization formulas. The velocity of sound of the homogenized brick block $c_{o,eff}$ and the attenuation coefficient $\alpha_{0,eff}$ were estimated by using Wiener's bounds and Lichtenecker's formula with various k parameters. Verification of the presented models with experimentally determined data will be carried out in the subsequent work, which will help to choose the most precise model. Such model will be then used for estimation of the effective parameters without necessity of performing time consuming experiments. Further experimental determination of the sound velocity and the acoustic attenuation coefficient of building materials will be carried out also due to the fact that such measurements were performed very rarely until now and reliable parameters for such materials are missing. In the following work, theoretical approach presented in this paper will be complemented by practical acoustic measurements in wide audible frequency range by means of piezoelectric transmitter-receiver measurements, verification of the model and optimization of the shape and spatial arrangement of cavities. With respect to the observation, brick blocks with enhanced audio properties will be designed and produced.

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