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Experimental-theoretical approach to the identification of effective sound attenuation panels from recycled materials

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One of the most important problems of our modern urbanized society is associated with unwanted and potentially dangerous noises. The necessity for establishment of pleasant and healthy living and working environment implies development of effective methods and materials to reduce noise. Prototypes of noise reducing multilayer panels made from recycled materials, consisting of an outer layer of melded recycled rubber with adhesive and an inner layer of frittered mineral wool of various densities and thickness of the layers are presented in this work. The acoustic characteristics of different materials and multilayer panels are studied. Experimental data for the noise reduction coefficient in the frequency range from 65 to 4000 Hz have been obtained using the two rooms method. A theoretical model for determination of the effective noise reduction of the panels based on the experimental data is developed. The results obtained can be applied in developing noise absorbing barriers to achieve control of the environmental noise.

Key words: sound attenuation panels, recycled materials

INTRODUCTION

One of the serious problems of our modern urbanized society is associated with unwanted and potentially harmful noise. The requirement for a pleasant and healthy living and working environment inspires development of effective ways and materials to minimize the noise pollution.

Many studies have been focused on development and analysis of sound absorbing devices made of a variety of porous materials such as foams, fibrous and granular materials, etc., because of their high sound absorption capacity [1]. Open-celled polyurethane foams are widely used as sound absorbing materials because of good sound damping, low thermal conductivity and low density. The performance of polyurethane foams has been improved by the incorporation of micro-sized fillers [2, 3]. The addition of nano-silica leads to the significant increase of sound absorption ratio due to the multilevel microstructures of the materials and properties of polymer microparticles.

Seddeq investigated the influence of various factors like fiber type, fiber size, material thickness, density, airflow resistance and porosity on sound absorption behavior of different fibrous materials [4].

Granular materials based on crumb rubber of scrap tires have been extensively applied for absorption of sound and reduction of noise due to their attractive characteristics including porosity, relatively simple processing and commercial availability. A number of studies deal with the investigation of the relation between the acoustic behavior of these materials and the processing parameters such as granulometry, binder type and concentration, compaction ratio and final thickness [5–8].

Recently, lots of interest arises to multilayered panels, which can be an alternative to the sound absorbing materials. A number of multilayered panel prototypes have been developed using various combinations of absorbing materials: rubber-fibers-rubber [9], rubber-fabric-rubber-cork [10] and chipboard-crumb rubber-chipboard [11].

The aim of the present study is to prepare sandwich-like sound absorbing panels based on recycled rubber as outer layers and shredded mineral wool as an inner layer, to investigate their sound transmission properties depending on the material characteristic, layer arrangement and thickness, and to compare the experimental measurements to the theoretical results. For this reason, an experimental setup and a theoretical model are developed to identify the effective properties of the panels under consideration. The results can be applied in the design of sound transmission barriers to achieve control of the environmental noise.

EXPERIMENT

When a sound wave reaches a solid body it splits into a reflected, an adsorbed and a transmitted waves.

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The fraction of the incident sound energy which is transmitted throughout the body is called the transmission coefficient or sound transmission loss R and can be expressed through the ratio of the sound pressures of the incident and the transmitted waves.

In this section, the sound transmission loss of single plates made of rubber waste or mineral wool as well as three kind of panels is studied experimentally.

Materials

Crumb rubber from retreaded car tires with density of about 1050 kg/m^3 are used in this study. The rubber particles are highly irregular in shape – crumbs (tapes) with dimensions of about $15 \times 2 \times 2$ mm.

Commercial diphenylmethane diisocyanate Desmodur® E22 (product of Bayer MaterialScience, Germany) is used as binder for consolidation of the recycled rubber particles.

Mineral wool slabs with density of about 150 kg/m^3 and thicknesses of 30 mm (product of Knauf Insulation GmbH, Austria) are widely used for production of heat and isolation products. The technological wastes of such kind of production are broken up into smaller particles and used for preparation of panels. The diameter of the mineral wool fibers is about 6–10 μm.

Sample preparation

The plates for the outer layer are prepared by compression moulding of crumb rubber. The composition ratio between the binder and rubber particles is 10:90 and the amount of spray water required for polymerization of the binder is 0.05%. The reaction between water and binder creates foam in the interstices between the rubber particles. The mixture is hot compression molded at pressure of 8 MPa and temperature of 100°C during 10 min by means of a hydraulic press (Metallic 63, Russia). The pressed plates are $480 \times 480 \times 30$ mm of dimensions and overall density in the range from 680 to 810 kg/m^3. These values of overall density mean that the plate macrostructure contains a large percentage of air voids.

The inner layer consists of fragmented mineral wool slabs and represents a set of continuous filaments that trap air between them.

For easy reference later, the following notation is used: $R1$, $R2$ and $R3$ are rubber plates of density 680, 710 and 810 kg/m^3, respectively; $MW1$ and $MW2$ refer to aggregations of mineral wool particles of density 50 and 100 kg/m^3, respectively, whereas MW refers to a mineral wool plate of density 150 kg/m^3.

Panel configuration

The multilayered sound absorbing panels developed in this study are sandwich-like type with outer layers from recycled rubber plates and an inner layer from mineral wool (Fig. 1). The arrangement of the multilayered panels and the characteristics of separate materials are given in Fig. 2.

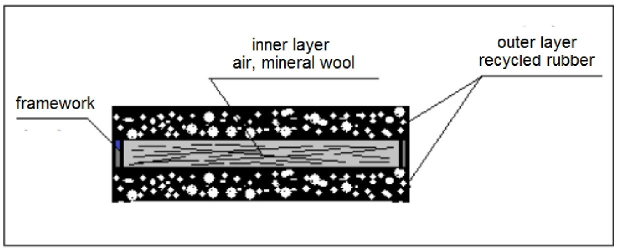


Fig. 1. Schema of multilayered sound absorbing panel.

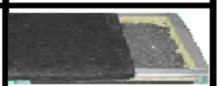
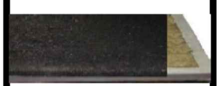
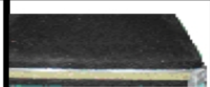
	Outer layer	Inner layer	Outer layer	Code	
1	Rubber plate ρ=710 кg/m^3	Air	Rubber plate ρ=710 кg/m^3	R2-A-R2	
2	Rubber plate ρ=710 кg/m^3	Mineral wool MW1 ρ=50 кg/m^3	Rubber plate ρ=710 кg/m^3	R2-MW1-R2	
3	Rubber plate ρ=710 кg/m^3	Mineral wool MW2 ρ=150 кg/m^3	Rubber plate ρ=710 кg/m^3	R2-MW2-R2	

Fig. 2. Arrangement of the multilayer panels and characteristics of the invloved materials.

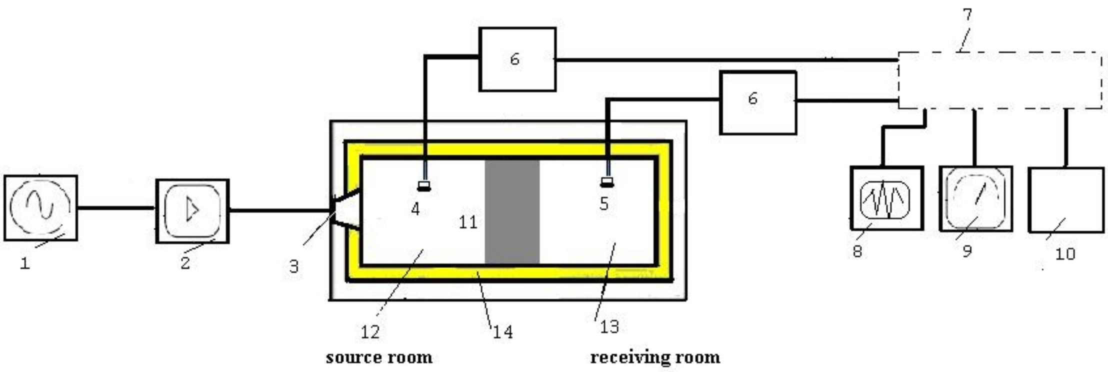


Fig. 3. Experimental setup: 1 – sound generator, 2 – amplifier, 3 – loudspeaker, 4 – reference measuring microphone, 5 – receiving microphone, 6 – microphone amplifiers, 7 – filters, 8 – digital scope, 9 – sound pressure measuring device, 10 – voltmeter, 11 – test specimen, 12 – source room, 13 – receiving room, 14 – sound absorbing walls.

Experimental setup

The experimental setup is shown in Figure 3. The experimental transmission loss measurements are carried out according to the procedures for field measurements of airborne sound insulation between two rooms [12, 13]. One of them (source room) contains the loudspeaker that creates a uniform sound field. The reference microphone measures the pressure of incident sound wave. Another microphone, placed in the receiving room, measures the pressure of the sound wave passed through the test specimen. The volume of the rooms is selected depending on the tested materials as well as the range of the frequencies under consideration. The cameras have thick walls, insulated with sound absorbing material. Thus, the generated sound field can be considered as homogeneous and isotropic and the transmission of the sound outside the test specimen is satisfactory reduced.

The sound transmission loss is determined in the frequency range from 65 to 4000 Hz by

$$R = L_{P_1} - L_{P_2} + 10\lg \frac{S}{A_2}$$

where L_{P_1} and L_{P_1} are the average sound pressure levels in the source and receiving rooms, respectively, S is the area of the test partition and A_2 is the absorption area of the receiving room. Each result is the averaged value from 5 measurements.

Experimental observations

The results from sound transmission loss measurements for the single plates $R1$, $R2$, $R3$ and MW are

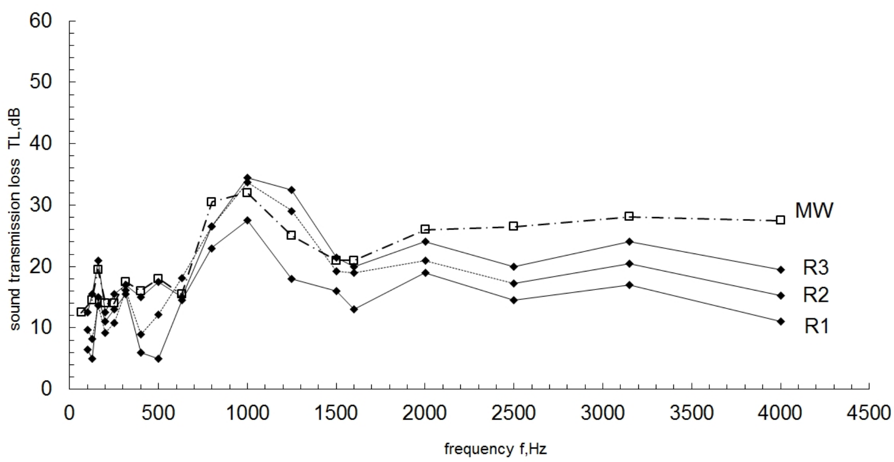


Fig. 4. Sound transmission loss as a function of frequency for single layer panels.

shown in Fig. 4. Three zones can be distinguished observing this graphic. A kind of chaotic behaviour is observed in the frequency range 65–500 Hz where the average value of R is found to be 15 ± 1 dB for the mineral wool specimen and 12 ± 2 dB – for the three rubber plates. A peak at approximately 1000 Hz is observed in the frequency range between 600 and 1500 Hz, and constant behaviour of the mineral wool specimen and small fluctuations for the rubber specimens are manifested in the second half of the frequency region under consideration. In general, the sound transmission loss increases with the density of rubber plates but it is apparent, that the density slightly changes this parameter.

The three-layer panels shown in Fig. 2 exhibit much higher noise reduction capability in the frequency range under consideration as can be observed in Fig. 5. This graphics comprises two regions – a monotone one below 1400 Hz and an almost constant one for the other frequencies, except for the $R2-MW1-R2$ panel exhibiting some variance. The use of the air gap between rubber plates rises the transmission loss from 20 dB (initial average value for a single plate) to above 40 dB.

The application of mineral wool as inner layer improves acoustic insulation in comparison with the case of air gap, especially for frequencies above 2500 Hz. The density of the inner layer also influences the results. The average values of the sound reduction by panels with inner layer from mineral wool type $MW1$ and $MW2$ are 45 dB and 48 dB, respectively.

NUMERICAL SIMULATION OF SOUND WAVE PROPAGATION WITHIN PLATES AND PANELS

Equations of motion

In this section the rubber and the mineral wool components of the panel are considered as homogeneous bodies. It is supposed that the incident wave front is a plane parallel to the panel external surface. Thus, the displacement field **u** within the panel is

$$\mathbf{u} = \mathbf{u}(x,t), \qquad \mathbf{u} = (u,v,w), \tag{1}$$

where x is the coordinate orthogonal to the largest panel side, t is the time, u is the displacement component parallel to x, while v and w are the displacements orthogonal to x.

Since the acoustic motions of the rubber or mineral wool particles are small, a linear strain-displacement hypothesis is considered, namely [14]

$$\begin{aligned} \varepsilon_{11} &= \frac{\partial u}{\partial x}, \qquad \varepsilon_{22} = \varepsilon_{33} = 0, \\ \varepsilon_{12} &= -\frac{\partial v}{\partial x}, \qquad \varepsilon_{13} = \frac{\partial w}{\partial x}, \qquad \varepsilon_{23} = 0, \end{aligned} \tag{2}$$

where ε_{ij} are the components of the strain tensor.

The propagation of acoustic waves within the panels studied here is supposed to be described by a linear elastic material model. The respective constitutive relations for each layer of the panel are [14]

$$\begin{aligned} &\sigma_{11} = (\lambda + 2\mu)\varepsilon_{11}, \qquad \sigma_{22} = \sigma_{33} = \lambda\varepsilon_{11}, \\ &\sigma_{12} = 2\mu\varepsilon_{12}, \qquad \sigma_{13} = 2\mu\varepsilon_{13}, \qquad \sigma_{33} = 0, \end{aligned} \tag{3}$$

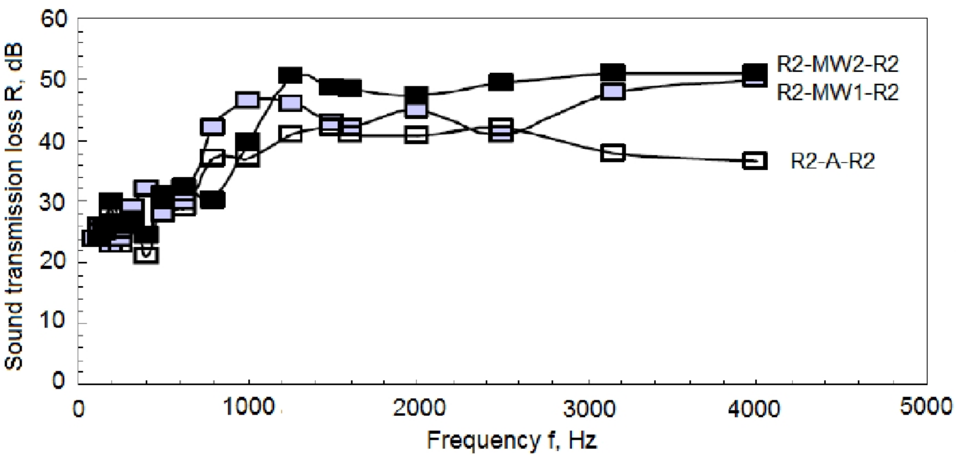


Fig. 5. Sound transmission loss as a function of frequency for absorbing 3 layers panels.

where σ_{ij} are the components of the stress tensor, and (λ, μ) are the Lame coefficients of the material of the particular layer.

The decay of the acoustic waves within the panels under consideration is supposed to be proportional to the velocity of the material particles with coefficients that have to be determined such that the ratio of the energies (amplitudes) of the incident and transmitted waves be the same as the experimentally observed one. Thus, the equations of motion read [14]

$$\begin{aligned}
\frac{\partial \sigma_{11}}{\partial x} + \kappa_j \frac{\partial u}{\partial t} &= \rho_j \frac{\partial^2 u}{\partial t^2}, \\
\frac{\partial \sigma_{12}}{\partial x} + \kappa_j \frac{\partial v}{\partial t} &= \rho_j \frac{\partial^2 v}{\partial t^2}, \\
\frac{\partial \sigma_{13}}{\partial x} + \kappa_j \frac{\partial w}{\partial t} &= \rho_j \frac{\partial^2 w}{\partial t^2},
\end{aligned} \tag{4}$$

where (κ_j, ρ_j) are the damping coefficient and the density of the material of the layer j.

Substituting the expressions (2) and (3) in the equations of motion (4), one obtains three independent wave equations of form

$$\begin{aligned}
(\lambda_j + 2\mu_j) \frac{\partial^2 u}{\partial x^2} + \kappa_j \frac{\partial u}{\partial t} &= \rho_j \frac{\partial^2 u}{\partial t^2} \\
\mu_j \frac{\partial^2 v}{\partial x^2} + \kappa_j \frac{\partial v}{\partial t} &= \rho_j \frac{\partial^2 v}{\partial t^2} \\
\mu_j \frac{\partial^2 w}{\partial x^2} + \kappa_j \frac{\partial w}{\partial t} &= \rho_j \frac{\partial^2 w}{\partial t^2},
\end{aligned} \tag{5}$$

where $j = 1, 2, 3$ identify the material properties of the panel layers.

Initial, boundary and compatibility conditions

Let the panel be of width L and the other two dimensions be much larger than the width meaning that without loss of generality it may be considered infinite in these directions. It is supposed that initially the panel is at rest and let $t = 0$ be the time, when a flat incident wave reaches its left surface. Then, the initial conditions are

$$\begin{gathered}
u(0,0) = \widehat{u}, \qquad u(x,0) = 0 \quad \text{for} \quad x > 0, \\
v(x,0) = w(x,0) = 0, \\
\frac{\partial u}{\partial t}(x,0) = \frac{\partial v}{\partial t}(x,0) = \frac{\partial w}{\partial t}(x,0) = 0,
\end{gathered} \tag{6}$$

for the left layer, where $\widehat{u} > 0$ is the magnitude of the incident wave, and

$$\begin{gathered}
u(x,0) = v(x,0) = w(x,0) = 0, \\
\frac{\partial u}{\partial t}(x,0) = \frac{\partial v}{\partial t}(x,0) = \frac{\partial w}{\partial t}(x,0) = 0,
\end{gathered} \tag{7}$$

for the other panel layers.

In order to model the experimental setting, it is supposed that the panel surfaces are free of supports and tractions. Then, the boundary conditions read

$$\begin{aligned}
\frac{\partial u}{\partial x}(0,t) = \frac{\partial v}{\partial x}(0,t) = \frac{\partial w}{\partial x}(0,t) = 0, \\
\frac{\partial u}{\partial x}(L,t) = \frac{\partial v}{\partial x}(L,t) = \frac{\partial w}{\partial x}(L,t) = 0,
\end{aligned} \tag{8}$$

where L is the thickness of either the single plate, or the panel under consideration.

Let us recall that our main interest in this study is determination of the noise transmittal properties of the panels developed here. Thus, it suffices to consider only one passing of the sound wave through the panel width and to compare the amplitudes of the incident and transmitted waves. Therefore, the computations are limited to the time interval necessary for the wave to traverse the panel width.

In the multi-layered panels considered here, the adjacent layers are not firmly fixed. Then, only the normal displacement and stresses across the common boundary between adjacent layers should be continuous, implying the compatibility conditions of form

$$\begin{aligned}
u_k(x_0,t) &= u_{k+1}(x_0,t), \\
\frac{\partial u_k}{\partial x}(x_0,t) &= \frac{\partial u_{k+1}}{\partial x}(x_0,t),
\end{aligned} \tag{9}$$

where x_0 denotes the boundary between layers k and $k+1$, and it is worth noting that the second relation involves the left derivative of u_k and the right derivative of u_{k+1}.

Numerical results

Let T and c such that $T = L/c$, $c = \sqrt{\dfrac{\lambda + 2\mu}{\rho}}$ be the time necessary for the wave to traverse the body thickness and the sound velocity in the body material. The routine NDSOLVE of MATHEMATICA®is used to solve numerically the foregoing initial-boundary value problem. The right-hand side of the initial condition that suffers a jump at $x = 0$ is approximated by the function $\exp(-10x^2)$. Here, this numerical scheme is applied to single rubber and mineral wool plates as well as to the panels, studied experimentally in

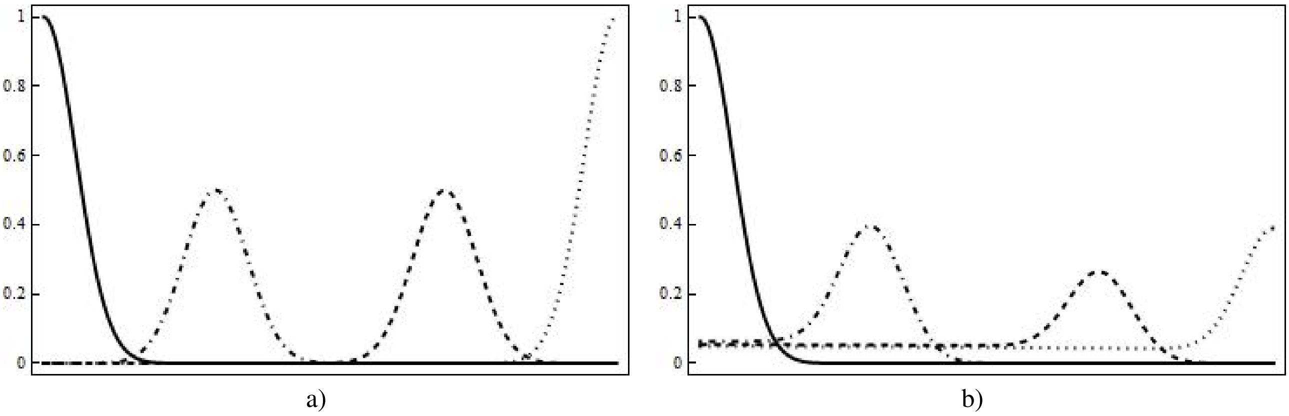


Fig. 6. Wave profiles corresponding to $t = 0$ (solid), $t = 0.3T$ (dot-dashed), $t = 0.7T$ (dashed) and $t = T$ (dotted): a) $\kappa = 0$; b) $\frac{\kappa L}{\rho c} = 0.029$.

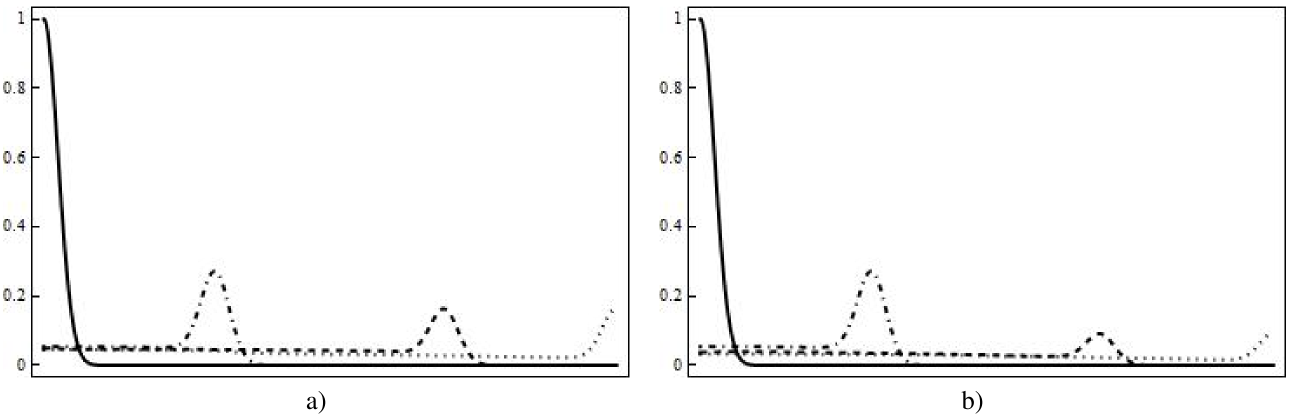


Fig. 7. Wave profiles corresponding to $t = 0$ (solid), $t = 0.3T$ (dot-dashed), $t = 0.7T$ (dashed) and $t = T$ (dotted): a) Inner layer – MW1; b) Inner layer – MW2.

Section 2. The purpose is to identify the damping coefficients κ of each material and the effective transmission loss of the panels.

First, plates by the three recycled rubber waste materials $R1$, $R2$ and $R3$ are studied. Typical picture of the propagation of a wave of initial magnitude $\widehat{u} = 1$ through the thickness of the $R2$ plate are shown in Figure 6. The case a) is presented only for verification of the numerical scheme and it displays the wave propagation if the damping is $\kappa = 0$, that is the classic solution of the undamped wave equation. The case b) corresponds to the wave profiles for damping coefficient $\kappa/(\rho c^2) = 0.029$, identified by matching the numerical results to the average value of the transmission loss results obtained experimentally and presented in Fig. 4.

Next, the panels with inner layers of $MW1$ and $MW2$ that are of better insulating properties obtained experimentally are studied numerically. The results from the numerical simulation are shown in Fig. 7. The dimensionless numerical solutions satisfy boundary and initial conditions exactly and the differential equation within a precision of 10^{-3}.

The amplitude reduction of the three-layer panels is apparent, comparing Fig. 7 to Fig. 6b. The amplitude of the incident wave at both figures is 1, whereas the amplitudes of the transmitted waves are 0.390 (Fig. 6b), 0.165 (Fig. 7a) and 0.091 (Fig. 7b).

CONCLUSIONS

The present study concerns a particular aspect on the way to manage two important problems of this century – the need to recycle the waste products and to reduce the noise pollution. Here, the waste of the isolation production using mineral wool cuts and rubber from retreading car tires are used to develop a special kind of sound barriers suitable for application along highway roads. The rubber and mineral wool wastes are cut in small pieces. Plates of large volume fraction of air are produced and used as containers of the mineral wool cuttings as is shown in Fig. 1.

The experimental results show that the crumb rubber panels exhibit good noise reduction capability. Even greater sound reduction can be achieved by the arrangement of multilayer panels made from such recycled materials. An appropriate choice of the material, thickness and density will improve the insulating quality and sound transmission loss of the suggested barriers. The results presented here show that using the panels developed within this study one can achieve more than ten times reduction of the amplitude of the sound wave as can be observed in Fig. 7b.

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ЕКСПЕРИМЕНТАЛНО-ТЕОРЕТИЧЕН ПОДХОД ЗА ИДЕНТИФИКАЦИЯ НА ЕФЕКТИВНОТО ШУМОЗАГЛУШАВАНЕ НА ПАНЕЛИ ОТ РЕЦИКЛИРАНИ МАТЕРИАЛИ

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(Резюме)

Един от сериозните проблеми на съвременното ни урбанизирано общество е свързан с нежелани и потенциално опасни шумове. Изискванията за по-приятна и здравословна жизнена и работна среда налагат необходимостта от разработване на ефективни начини и материали за намаляване на шума.

В настоящата работа се предлагат прототипи на многослойни звукопоглъщащи панели от рециклирани материали, които се състоят от външен слой пресована рециклирана гума с адхезив и вътрешен слой раздробена минерална вата или нетъкан текстил (полиестерна вата) с различна плътност и дебелина на слоевете.

Изследвани са акустичните характеристики на отделните материали и многослойните панели. Получени са данни за коефициента на звукоизолация по метода на "двете камери" в честотния интервал от 100 до 4000 Hz.

Разработен е теоретичен модел за идентифициране на ефективните свойства на панелите при поглъщане на преминаваща през тях звукова вълна, който е потвърден от експерименталните изследвания. Получените резултати са приложими при конструиране на звукопоглъщащи бариери за постигане на контрол на шума в околната среда.