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SOUND ABSORPTION PROPERTIES OF MATERIALS BASED ON RECYCLED PLASTIC GRANULE MIXTURES

Andrea BISKUPIČOVÁ[1*], Miriam LEDEREROVÁ[1], Stanislav UNČÍK[1], Christ GLORIEUX[2], Monika RYCHTÁRIKOVÁ[2]

Abstract

This article reports on impedance tube measurements of the sound absorption coefficient α (-) of selected recycled foam plastics, i.e., ethylene-vinyl acetate (EVA), polyvinyl chloride (PVC), polystyrene (PS), and polypropylene (PP), in different mixtures with a binding adhesive. The effect of the thickness of the sample on the sound absorption spectrum as well as the variability in absorption across the different samples of the same composition and thickness are discussed. For the EVA/PP and PS/PP mixtures, the spectrum is characterized by two peaks that shift as the thickness is changing. These mixtures were also found to be the most absorbent across the whole audible frequency range.

Address

[1] Dept. of Building Materials, Faculty of Civil Engineering, Slovak University of Technology, Bratislava, Slovakia
[2] Dept. of Physics and Astronomy, Laboratory of Acoustics, KU Leuven, Belgium, Faculty of Architecture, KU Leuven, Belgium

* ***Corresponding author:*** andrea.biskupicova@stuba.sk

Key words

- Sound absorption,
- Recycling,
- Metamaterials.

1 INTRODUCTION

In terms of sound absorption, recycled porous materials achieve comparable values to natural materials (Desarnaulds et al., 2005). Moreover, some of these recycled materials have been reported to improve thermal insulation properties (Gregorova et al., 2017; Biskupicova et al., 2018; Daubnerova et al., 2018; Sukontasukkul et al., 2009; Petrella et al., 2020).

The strength characteristics (Siddique et al., 2008; Batayneh et al., 2007; Lukic et al., 2016), as well as the acoustic properties of porous materials and related composites have been investigated by various researchers (Needhidasan et al., 2020; Moreno-Sierra et al., 2020; Ozkal et al., 2020; del Rey et al., 2012; Dunn et al., 1986; Liu et al., 2017; Oancea et al., 2018; Zulkifli et al., 2008). For more detailed information on the state of the art, see Biskupičová et al. 2020.

In this work, we address the issue of to what extent materials made of bound plastic grains that have been recycled from plastic waste could be used for acoustic absorption purposes in acoustic applications for rooms. The acoustic absorption of different composites based on ethylene-vinyl acetate (EVA), polyvinyl chloride (PVC), polystyrene (PS), and polypropylene (PP) grains connected by a binding adhesive was determined for different mixing compositions. The measurements of the acoustic impedance and absorption for perpendicularly incident sounds were performed by means of an impedance tube.

2 DESCRIPTION OF THE SAMPLES

Five types of samples were investigated, each consisting of a different mixture of recycled plastics in a ratio of 1:1 (each mixture consisting of 2 litres of filler and 0.15 litres of binder). The first material was a mixture of EVA/PS, as shown in Fig.1a. The grain size of both components varied between 4 and 8 mm. The second material consisted of EVA (4-8 mm grains) and PVC (0-4 mm grains), as shown in Fig.1b. The third sample (Fig.1c) was a mixture of PVC (0-4 mm grains) with PS (4-8 mm grains). Sample 4 was made of EVA and PP, both with grain sizes between 4 and 8mm (Fig.1d). The fifth material was based on 0-8 mm polyurethane (PU) grains mixed with PP grains (4-8 mm), as shown in Fig.1e. The Conipur 360 PU adhesive (also known as 4.4´ MDI) was used as a binder in all of the 5 material types. The samples were produced in the Laboratory of the Department of Building Materials at the Faculty of Civil Engineering at STU in Bratislava. The production process of the samples was done manually. In order to reduce the uncertainty of the production process, three samples were made for the composition. All the sam-

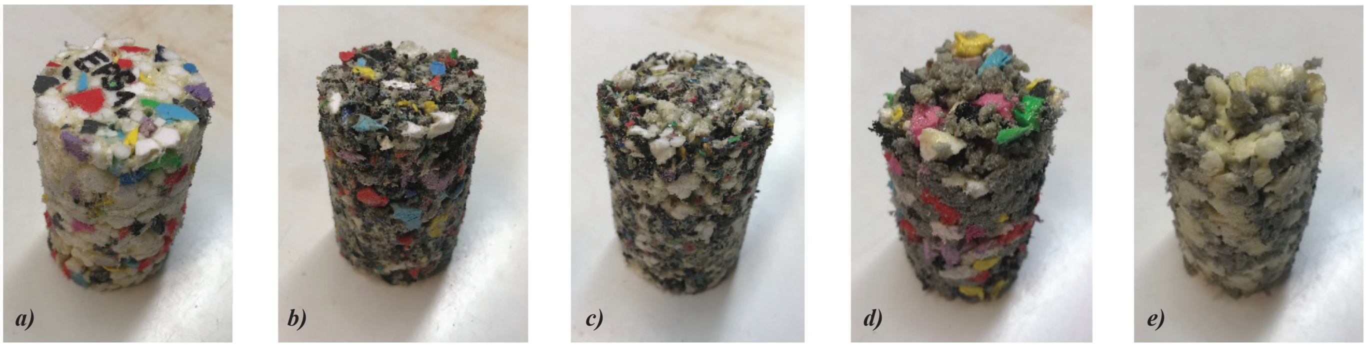

Fig. 1 *The five types of samples measured. From left to right: a- EVA/PS; b-EVA/PVC; c- PVC/PS; d- EVA/PP; e- PU/PP*

ples had a diameter of 44 mm and an initial thickness of 65 mm. All of the samples were then stored in a laboratory environment for 24 hours (temperature t=20°C, relative humidity φ=50%). We observed that, due to gravitation, the glue had a tendency to accumulate during the binding process towards the bottom of the mixture. Therefore, in a later stage of the measurements, the samples were thinned, first to a 50 mm and then to a 30 mm thickness, by cutting the bottom of the sample, and the acoustic absorption of the remaining parts was then determined. Therefore, one of the hypotheses was that the thinner samples would have slightly different behaviour than the ones with the original thickness.

3 MEASUREMENTS

An impedance tube with two microphones was used to measure the sound absorption coefficient α (-) (Fig. 2). This impedance tube is homemade and was validated in a round robin test in the framework of the DENORMS COST action. More detailed information about this method can be found in Koruk (2014). The measurements were performed according to ISO 10534-2 in the Laboratory of Acoustics of the Department of Physics and Astronomy at KU Leuven (Belgium). For each mixture, three samples were characterized.

4 RESULTS AND ANALYSIS

The average absorption spectra and some comparisons between the three samples of the same composition are depicted in Figs. 3 to 10. The absorption results are discussed below in terms of (i) the effect of cutting the glue-rich bottom of the sample and (ii) the effect of the sample´s composition.

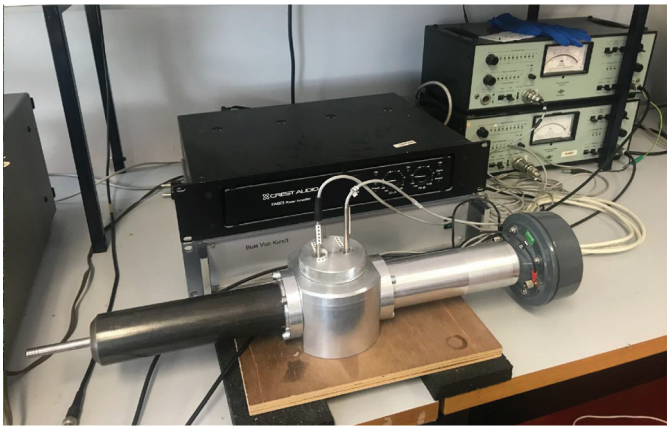

Fig. 2 *Measurement set up: impedance tube*

Before analyzing the differences between the samples of different thicknesses, it is useful to look at Fig. 3b, which shows that the absorption spectra of the 3 different 65mm - thick samples are quite different. This indicates that their porosity, which is a key factor for the absorption, significantly varies. We have observed from a visual inspection of the cross sections of the samples, that in some regions of the samples, the glue closes the space between the grains, so that these regions can no longer contribute to the absorption (which is based on the friction between the vibrating air particles and grain surfaces in pores that can be reached by the incident sound waves). Although the glue is mainly concentrated in the bottom of the samples, there are substantial differences in its distribution. This is a consequence of the difficulty in controlling the viscous flow of glue in between the grains during the production process.

The differences in absorption between the original 65 mm - thick EVA/PS samples with the samples of which the bottom 15 mm (50 mm thickness) and the bottom 35 mm (30 mm thickness) have been removed are shown in Fig. 3a. The two main factors responsible for these differences are i) the volume of absorption-inducing open pores accessible for the incident acoustic waves and the location of those pores in terms of their distance from the non-porous part of the sample (pores closed by glue) and ii) the hard backing of the impedance tube at the bottom side of the sample. The greater the volume of the accessible open pores, the higher the absorption. The thicker the accessible pore volume, the further from the sound-reflecting back of the sample that the incoming and reflecting waves can dissipate their acoustic energy and thus attenuate. It is known that the most efficient distances d_n from a hard reflector (the hard end of a tube or the glue-saturated part of the sample) for the porous material to absorb sound energy are odd multiples of a quarter wavelength ($d_n=(2n+1)\lambda/4$, with $2n+1$ odd numbers and λ the wavelength), due to the corresponding maxima of the particle velocity standing waves (resulting from the interference between the incoming and reflected sound waves) at those locations. As a consequence, the thicker the open pore part of the sample, the longer the wavelengths that can be efficiently absorbed. This explains why in Fig. 3a, the absorption curves of the 50 mm and 65 mm samples are more pronounced at low frequencies (long wavelengths) than the one of the 30 mm sample. In spite of being thinner, the absorption peak around 2.3 kHz (corresponding with $\lambda/4$= 37 mm in the air) of the 30 mm sample exceeds the maximum absorption of the 65 mm sample. This is because the peak occurs at a higher frequency than that of the 65 mm sample, which occurs at around 0.7 kHz; the lower the frequency, the less effective the dissipation of the acoustic energy into frictional heat. The peaks for the 65 mm and 50 mm samples occurring at 0.7 kHz, which correspond to a value of $\lambda/4$=12cm in the air and which are substantially further from the back than the front of the sample, indicates that, due to the tortuosity of the material, the wavelength in the porous sample is shorter than the one in the air, thereby cor-

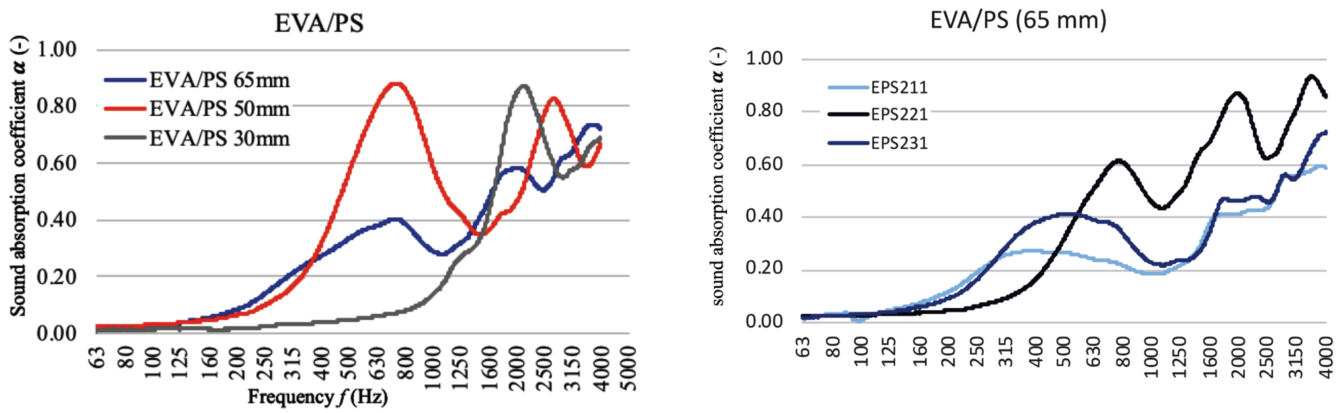

Fig. 3 *Absorption spectra of the EVA/PS mixtures for the samples of different thicknesses (left); Large variations in sound absorption are found between the three 65mm samples (right), in spite of their equal production steps*

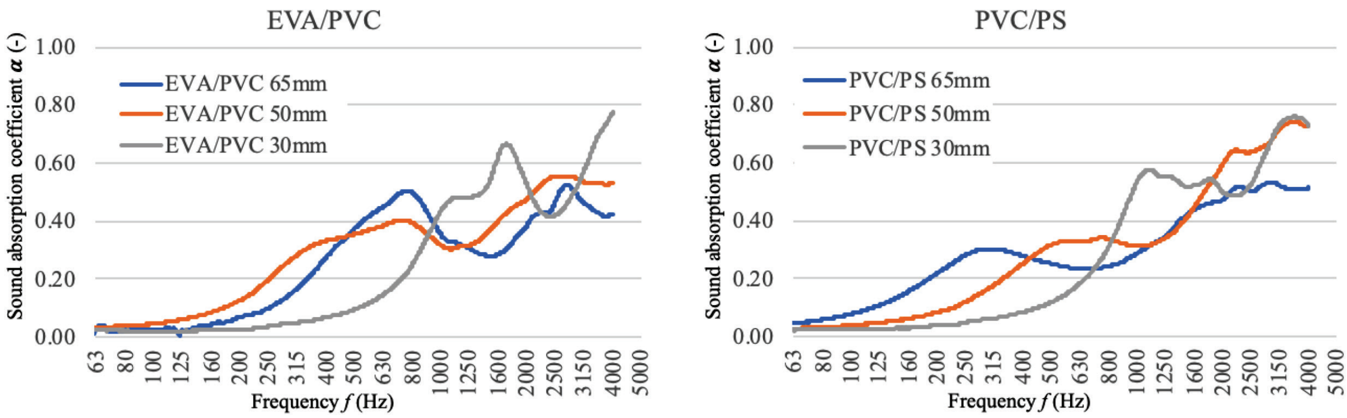

Fig. 4 *Effect of the thickness of the EVA/PVC material (left) and PVC/PS (right) on the sound absorption coefficient*

responding with a substantially slower speed of sound (Knapen et al., 2003).

Similar trends from changing the thickness (by removal of the bottom part of the sample) as the ones described above can be observed for the EVA/PVC and PVC/PS composites (Fig.4). However, the peaks are less pronounced, resulting in a globally lower amount of absorption. This is a consequence of the smallness of the PVC grains (between 0 and 4 mm), which can efficiently fill the pores between the larger grains of the EVA and PS (grain size between 4 and 8 mm), thus leaving less pore space and fewer possibilities for sound to enter the material via the pore channels and dissipate the energy. Interestingly, the lowest peak frequencies of the PVC/PS are substantially lower (about a 2) factor than the ones of the EVA/PVC.

Like the EVA/PS material, the samples made of the EVA/PP and PS/PP mixtures (Fig. 5) indicate a behaviour that is typical of composite materials made out of recycled granules (Asdrubali et al. 2012), with two clear maxima in the absorption spectrum, which shift towards lower frequencies with an increasing thickness of the sample. The peak frequencies of the PVC/PS are substantially lower (about a 2 factor) than the ones of the EVA/PP and EVA/PS, which correspond with a larger $\lambda/4$ value. This indicates that the speed of sound in the PVC/PS is lower than the one in the latter materials and can be explained by the more tortuous nature of the narrow air channels between the small and large grains in the PVC/PS. Unfortunately, as mentioned above, the narrow channels are also less permeable for sound, thereby keeping the absorption rather small (α_{max}=30% at the 280 Hz maximum).

The EVA/PP samples with 65 mm shows maximal α values (0.8) at frequencies of 500, 2000 and 4000 Hz. For frequencies above 300 Hz, the values are never lower than 0.38. The samples with a 50 mm thickness (after the cut part with the high adhesive concentration) showed a maxima around 1000 Hz and 3150 Hz with a local minimum (α=0.7) around 2 kHz (Fig. 5-left). The results suggest that a composite structure of the EVA/PP samples or PS/PP samples of different thicknesses would yield a fairly high absorption for all the frequencies above 300 Hz.

A comparison between samples with the same thickness, i.e., 65 mm, but different compositions, is shown in Fig. 6. The PS/PP composite (light orange) has the highest sound-absorbing properties among all the samples over the entire frequency range measured. A similar shape of the absorption spectrum, i.e., with peaks at 630 Hz and 2.5 kHz, but with about 10% lower values, is exhibited by the EVA/PP. The EVA/PVC and EVA/PS have their first maximum around 800 Hz (with α ~40-50%). For the PVC/PS composite, the absorption curve is horizontally compressed, thereby bringing the peaks to lower frequencies. This reflects a lower speed of sound and thus higher tortuosity, which can be explained by the more efficient pore filling of the combination of large and small grains. All the samples above 300 Hz have a sound absorption coefficient greater than 20%.

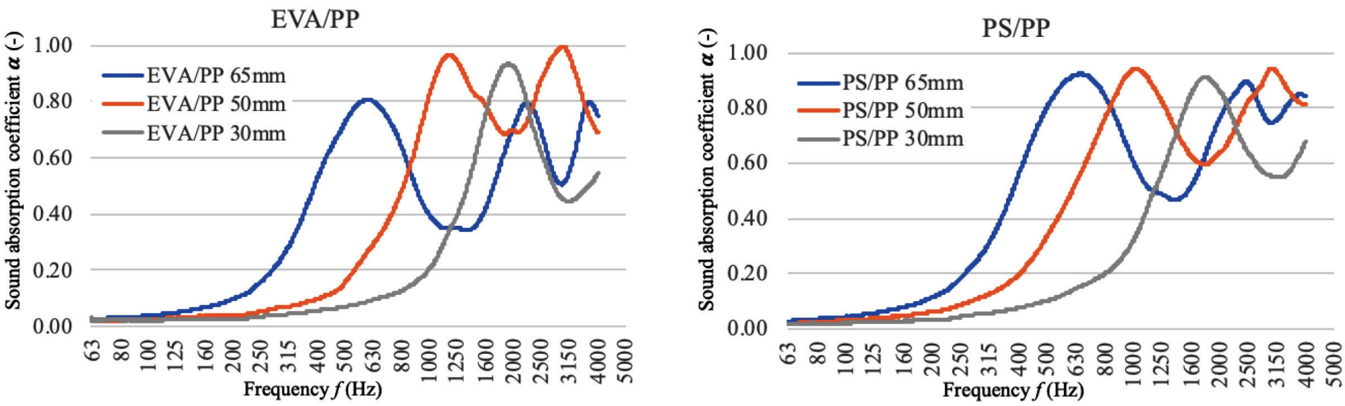

Fig. 5 *Comparison between the sound absorption spectra of the EVA/PP (left) and PS/PP composites (right), showing a clear decrease in the peak frequencies with increases in the thickness of the sample*

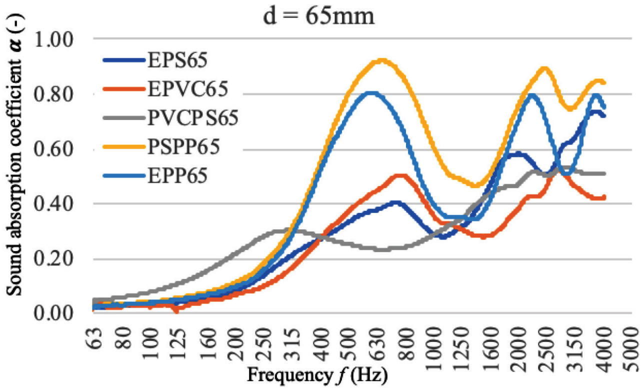

Fig. 6 *Comparison of the sound absorption spectrum of five different composite samples with a thickness of 65 mm*

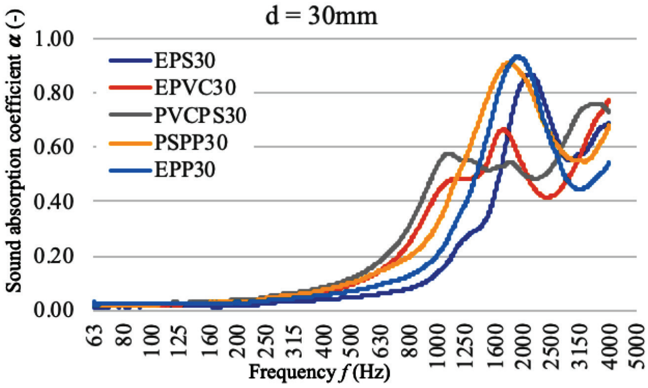

Fig. 8 *Comparison of the sound absorption spectrum of five different composite samples with a thickness of 30 mm*

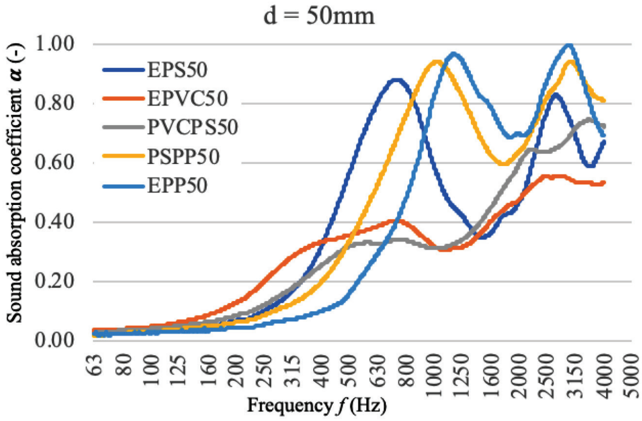

Fig. 7 *Comparison of the sound absorption spectrum of the five different composite samples with thicknesses of 50 mm*

The results of the measurement of the 50-mm thick samples are shown in Fig. 7. Here, the absorption of EVA/PS already exceeds 40% from 400 Hz and above, with a peak of 90% at 630 Hz. However, it drops again at around 1600 Hz to values slightly lower than 40%. The PS/PP only has α >40% above 500 Hz, with a maximum (α >90%) around 1 kHz. For high frequencies its absorption values never drop under 60%. The samples based on the EVA/PP have their lowest maximum at around 1.25 kHz. The differences in the frequency of the first absorption maximum can be expected to result from differences in the speed of sound and tortuosity of the respective materials. This is to be further confirmed by ultrasound measurements of the speed of the sound. As mentioned above, the two materials containing small PVC grains have less absorption because their pores are filled more, so that they are less permeable for sound and reflect it more.

The samples with a 30 mm thickness show a similar trend as their thicker versions (Fig. 8). The highest value of α was 1.6 – 2 kHz for most of the materials. Only the composite based on the PVC and PS shows a different behaviour. As mentioned earlier, it is not surprising that these thinner samples have less low frequency absorption than the thicker ones.

5 CONCLUSIONS

Five composite materials consisting of plastic grains (EVA, PP, PS, PVC) connected by glue have been examined. A clear difference in the acoustic absorption spectrum has been found between the mixtures containing only large grains (4-8 mm) and the mixtures containing both large and small (0-4 mm) grains. The latter ones are filled more, thereby resulting in more narrow pore channels, which in turn lead to a smaller permeability for acoustic waves and to a lower speed of sound. As a consequence, they reflect more and absorb less sound, but their maximum sound absorption occurs at lower frequencies than those of the other mixtures.

The results obtained for the 65 mm samples and the shorter ones, which were obtained by cutting their bottom parts, also show that in the production of the samples, the glue that is needed to connect the grains has a tendency to accumulate in the bottom, thus closing the pores and reducing the absorption. The downward flow of the glue during the production process is also not perfectly regular, which causes inhomogeneities in the glue content and thus in porosity and acoustic behaviour.

Finally, the sound absorption of the newly developed recycled materials measured by the impedance tube can serve for the design of noise barriers and sound-absorbing building facades and can be considered as a good initial value of sound absorption suitable for room acoustic predictions. In order to obtain more accurate values for room impulse response predictions, additional measurements in diffuse field would need to be performed.

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