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Research Paper

Sound Insulation Properties of Sound-Reduction Louvers with Innovative Devulcanized Rubber

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The growing amount of used tires presents many environmental challenges around the world. Therefore, new ways to reuse used tires are being sought. One of the uses of waste tires is in sound-insulating constructions. Waste tires can be shredded into granules, which can be further devulcanized to increase their porosity. These granules can then be glued to panels and used in sound-insulating structures. Acoustic louvers were investigated in this study, with the louvers' plates covered with rubber granule panels. Sound absorption parameters of rubber granule panels were tested across frequency bands ranging from 160 Hz to 5000 Hz. The results showed the normal incidence sound absorption coefficient reached 0.87–0.96 at 3150 Hz for 12 mm rubber granule plates. Measurements were conducted in a semi-anechoic chamber. The study has shown that rubber louvers can reduce the sound pressure level by 8 dB–12 dB, depending on the composite of the rubber granule panels and the tilt angle of the louvers' plates.

Keywords: acoustical louvers; rubber; sound absorption; insertion loss.

1. Introduction

Globally, approximately 0.7–1 billion new tires are produced each year due to the growing number of vehicles. Today, several approaches are taken to address the end-of-life tire (ELT) problem: reuse (5 %–23 %), recycling (3 %–15 %), and recovery (25 %–60 %) (Dissanayake *et al.*, 2021). However, more than 30 % of used tires still end up in landfills or are discarded as untreated waste (Karakurt, 2015). Due to increasing environmental pollution and the European Union's directives banning the disposal of tires in landfills, there is a growing interest in finding ways to reuse or recycle tires to achieve circular economy goals (Nacif *et al.*, 2013; Corredor-Bedoya *et al.*, 2017).

The accumulation of untreated tires, a non-biodegradable substance, is a major concern in many countries. Long-term storage of tires in landfills affects ecosystems, pollutes the environment, and creates a high risk of fire (Güneyisi, 2010; Siddique, Naik, 2004). Recycled rubber has good acoustic properties due to its porous structure and can therefore be recycled and used in construction materials, industry and various structures. This helps in protecting land resources and maintaining ecological balance (Gandoman, Kokabi, 2015).

Noise is considered to be one of the most important elements of environmental pollution, caused by different sources: cars, air transport, and industrial machinery (Dissanayake *et al.*, 2021). Noise does not only cause inconvenience in everyday life but is also harmful to our health. Noise is a form of energy that travels through solid bodies, liquids and gases, forcing particles to vibrate in longitudinal waves. To reduce the environmental impact of used tires, ways to recycle them efficiently and use them in production are being pursued. Granules, steel wires, and tire fibers are typical materials derived from ELT treatment (Landi *et al.*, 2018). One of the most popular methods is the incorporation of rubber granules into concrete mixes, which allows to develop new cement products for the construction of civil buildings. However, such composites are found to be weaker than pure concrete (Karakurt, 2015). Nevertheless, according to the researchers, different strength characteristics of the products can be obtained by using different rubber granules. Products with smaller particle granules have better strength properties than products with larger granules (Su *et al.*, 2015). Studies show that cement incorporating rubber granules absorbs sound more efficiently than conventional cement products, due to its higher porosity (Khaloo *et al.*, 2008).

There are many researchers who investigated the acoustic properties of rubber, since good sound attenuation of rubber is one of its characteristic advantages over many other materials available for acoustic applications. Swift *et al.* (1999) investigated noise barriers made of recycled rubber granulates, finding that the adhesive part of the composite does in fact reduces sound absorption. Low-frequency acoustic properties of honeycomb silicone rubber acoustic metamaterials were investigated by Gao and Hou (2017). Maderuelo-Sanz *et al.* (2012) developed a sound absorber by using waste tire rubber. Further investigations were conducted on acoustic metamaterials combining waste rubber (fibers or particles from waste tires or other products) with other substances such as plant flours or fibers, polypropylene or polyethylene, where rubber acts as an acoustic reinforcement unit (Xu *et al.*, 2018). Rubber granulometry has been found to influence sound-absorbing behaviours. Bujoreanu *et al.* (2017) investigated an experimental acoustic system with rubber particles by additionally using different backing plates including plasterboard, OSB, and polystyrene. Segura-Alcaraz investigated rubber-fiber-rubber layered construction panels as sound absorbers by using rubber from scrap tires and recycled fibers (Juliá *et al.*, 2013). Hong *et al.* (2007) mixed waste rubber particles with polymer porous foams. Kosała (2019) investigated the sound insulation properties of two-layer baffles consisting of rubber and steel, which exhibited good sound insulation properties.

Sound-absorbing materials can also be used in sound insulation constructions. Viveiros and Gibbs (2003) investigated the performance of acoustic louvers and found that, at frequencies where transmission is greatly unaffected by absorption (in this case below 1 kHz), the impulse measurement of transmission loss agrees well with insertion loss. This occurs due to the fact that, in this frequency region, insertion loss remains unaffected by the geometry of the louver and the angle of transmission. However, at frequencies where absorption and interference effects come into play (above 1 kHz), insertion loss becomes angularly dependent. Marriott (2012) concluded that the maximum sound insulation efficiency of acoustic blinds is achieved at high frequencies, potentially reaching up to 10 dB–12 dB.

In this work, we focus on innovative acoustic panels made of rubber granules that have good sound-absorbing properties. Recycling waste tires through mechanical and chemical devulcanization processes increases the porosity of the rubber granules, thereby improving their sound absorption properties. The granules are glued together with an innovative two-component polyurethane glue, enabling the creation of panels that can be affixed to the structure. Combining them with steel plates alows to make sound-absorbing plates, which can be used for sound absorbing and insulating barriers such as acoustic louvers. The aim of our work is to use such panels in constructions designed to reduce the noise generated by engineering equipment that requires ventilation. By covering gaps in the structure with rubber granulate panels, we anticipate achieving effective acoustic absorption and insulation.

2. Methodology

2.1. Research object

In this research, acoustic louvers consisting of seven metal steel plates covered on both sides with different composite 12 mm thick rubber panels were made and fixed onto a wooden frame (with adjustable panels angle) (Fig. 1). This louver design was intended for equipment that requires ventilation and air exhaust. The gaps between the panels allow for air to be removed, while also reducing the sound level when the panels are covered with sound-absorbing material. The structure was designed to have hydrophobic properties, be heat resistant, and absorb sound.

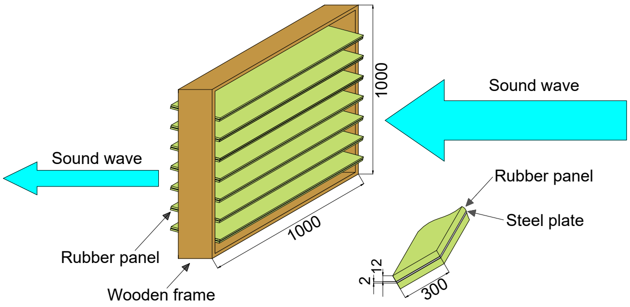

Fig. 1. Principal construction of acoustic louvers.

The plates were angled from 0° (horizontal) to 45° towards and away from the noise source (Fig. 2) in increments of 15° steps for each test angle increase.

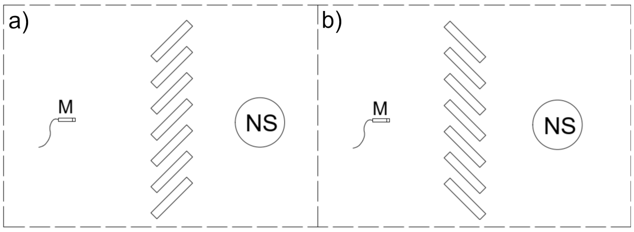

Fig. 2. Panels tilted in the following way: a) tilted towards the noise source; b) tilted away from the noise source.

2.2. Tested materials

Rubber granule panels were made from rubber granules obtained through ozonation after the rubber was separated from the tire structure. Two types of rubber granules were used for the production of rubber panels. The first type comprised mechanically removed primary tire tread, with the rubber granule size ranging from 4 mm to 15 mm (Fig. 3a). The second type consisted of mechanically removed and chemically treated tread layer, with the rubber granule size ranging from 1 mm to 3 mm (Fig. 3b).

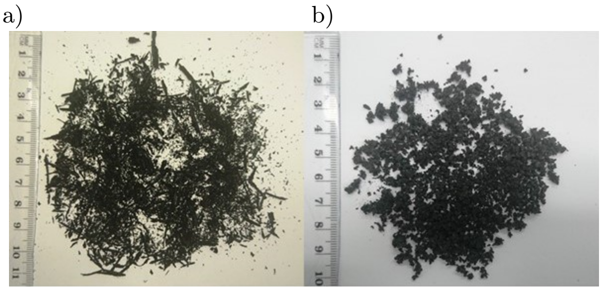

Fig. 3. a) Mechanically removed rubber;
b) chemically devulcanized rubber.

The chemical treatment of the rubber granules resulted in a higher porosity and a partially fibrous structure, thereby producing higher sound absorption. The difference between mechanically and chemically devulcanized rubber granules is shown in Fig. 4.

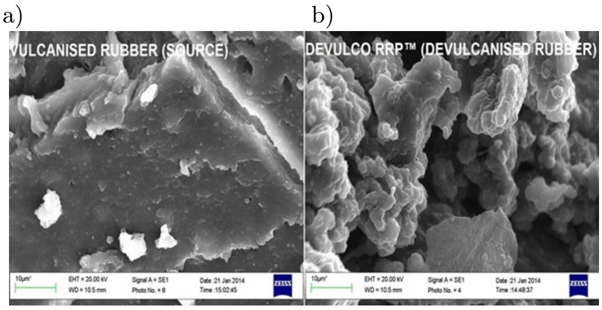

Fig. 4. a) Mechanically removed rubber;
b) chemically devulcanized rubber.

During the chemical devulcanization of rubber (converting it into devulcanized rubber flour), mechanical shear causes stresses in the bridges (S–S) between the rubber chains, while devulcanizing agent compounds promote the delocalization of these bridges (S–S), which results in the inhibition of rubber particle adhesion. This, in turn, results in a higher surface porosity of the rubber granules. The mechanically separated rubber granules form a straw-like structure, serving a reinforcing function, and corresponding to the properties of fibrous material in the rubber plate. Three types of rubber composites plates were produced using two types of rubber granules (Fig. 2). Plate no. 1 was made of mechanically removed rubber granules with a fibrous structure from elongated rubber granules. Plate no. 2 was made from chemically devulcanized rubber granules. Plate no. 3 was made by mixing both types of rubber granules in equal proportions. All three plates were bonded together using a special polymer glue.

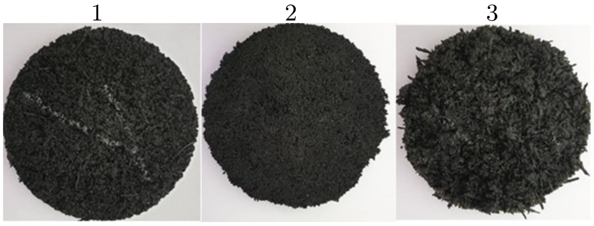

Fig. 5. Rubber granulate panels of different mixtures.

2.3. Sound absorption research methodology

Study of the sound absorption properties of rubber panels was carried out in the impedance tube according to International Organization for Standardization [ISO] (1998). The diameter of the impedance tube was 30 mm. Tests were carried out on round samples of 30 mm in diameter and 12 mm in thickness, placed in an impedance tube. Three microphones were used simultaneously to calculate two transfer functions H_{13} and H_{23} for measuring sound absorption properties, with the samples being rigidly backed. This method allowed to measure the normal incidence sound absorption coefficient from 160 Hz to 5000 Hz. The schematic experimental setup is shown in Fig. 6. The distance between microphone no. 1 and no. 2 X_{12} = 120 mm, between microphone no. 2 and no. 3 X_{23} = 20 mm, and the distance from the closest microphone to the sample X_{3S} = 60 mm.

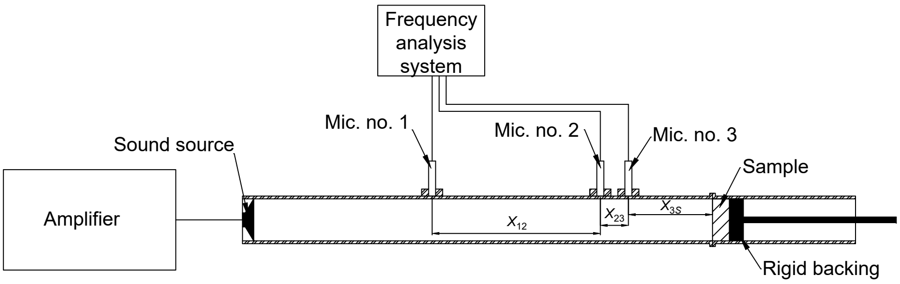

Fig. 6. Schematic experimental setup of impedance tube.

A sample was placed in the tube according to the procedures specified in (ISO, 1998). The transfer functions H_{13} and H_{23} in Eq. (1) between microphone positions were calculated as the pressure ratio between both microphones. The complex acoustic transmission function for the incident wave H_I and the reflected wave H_R was calculated according to Eqs. (2) and (3) (ISO, 1998):

$$H_{13} = \frac{p_3}{p_1}, \qquad H_{23} = \frac{p_3}{p_2}, \tag{1}$$

$$\begin{aligned} H_{I(160\text{–}1000\,\text{Hz})} &= \frac{p_{3I}}{p_{1I}} = e^{-jk_0(x_{12}+x_{23})}, \\ H_{I(1\text{–}5\,\text{kHz})} &= \frac{p_{3I}}{p_{2I}} = e^{-jk_0(x_{23})}, \end{aligned} \tag{2}$$

$$\begin{aligned} H_{R(160\text{–}1000\,\text{Hz})} &= \frac{p_{3R}}{p_{1R}} = e^{jk_0(x_{12}+x_{23})}, \\ H_{R(1\text{–}5\,\text{kHz})} &= \frac{p_{3R}}{p_{2R}} = e^{jk_0(x_{23})}. \end{aligned} \tag{3}$$

From Eqs. (2) and (3), the reflection coefficient was calculated according to Eqs. (4) and (5) (ISO, 1998):

$$R_{(160\text{–}1000\,\text{Hz})} = \frac{H_{13} - H_{I(160\text{–}1000\,\text{Hz})}}{H_{R(160\text{–}1000\,\text{Hz})} - H_{13}} e^{2jk_0(X_{12}+X_{23}+X_{3S})}, \tag{4}$$

$$R_{(1\text{–}5\,\text{kHz})} = \frac{H_{23} - H_{I(1\text{–}5\,\text{kHz})}}{H_{R(1\text{–}5\,\text{kHz})} - H_{13}} e^{2jk_0(X_{23}+X_{3S})}, \tag{5}$$

where R is the reflection coefficient and k_0 is the wavenumber in the air.

The normal incidence sound absorption coefficient was calculated according to Eq. (6) (ISO, 1998):

$$\alpha = 1 - |R|^2. \tag{6}$$

Results were presented as one-third octave frequency bands.

2.4. Methodology of measuring insertion loss

The study of insertion loss was performed in a semi-anechoic chamber. The chamber consisted of a solid floor, with walls and ceilings covered with acoustic foam to create an anechoic environment. The chamber had separate source and receiver rooms, each with dimensions of 2000 mm × 2500 mm × 2500 mm (L × W × H). A wall separating the two rooms had a test opening of 1000 mm × 1000 mm, where the acoustic louvers were mounted. The equipment used for measurements included an omnidirectional loudspeaker (Bruel & Kjaer Type 4292), an analyzer (Bruel & Kjaer 2270), and a microphone (Bruel & Kjaer Type 4189).

Two sound source positions in the source room and five microphone positions in the receiver room were designated. Insertion loss was calculated as the difference between the sound pressure level without the louver and the sound pressure level with the louver. Insertion loss was calculated according to Eq. (7) (as specified in (ISO, 2020)):

$$\text{IL} = 20 \log\left(\frac{p_{\text{without}}}{p_{\text{with}}}\right) = L_{p1} - L_{p2}, \tag{7}$$

where L_{p1} is the sound pressure level without the structure [dB] and L_{p2} is the sound pressure level with structure [dB].

Initially, the sound pressure level was measured without any sample, and then the tests were repeated with the test sample. Results were calculated according to Eq. (7).

The following conditions were maintained during the tests:

- distance between source and microphone: >0.5 m;
- measurement time: 30 s;
- white noise was used as the sound signal.

3. Results

3.1. Ray tracing

Ray tracing is a computational method that allows the prediction of wave propagation paths based on the shape of a structure and the properties of materials involved in absorbing and reflecting sound. This method allows for the analysis of how sound waves may change their direction of propagation or reflect off structures. In this study, wave propagation was analyzed during using Odeon 16.0 Auditorium software. The principle behind acoustical louvers relies on the ability to alter the tilt angle of the plates, thereby changing the direction of sound wave propagation. Additionally, using sound-absorbing materials, it becomes possible to absorb a portion of the sound energy. In this part of the research, the propagation of waves through the structural plates was analyzed by changing the tilt angle of the construction plates from 0° to 45°. The angle was adjusted every 15°, with the plates tilted both towards and away from the noise source.

The wave propagation analysis (Fig. 7) shows that when the plates were in the horizontal 0° position, the main proportion of sound waves was reflected from the plates only once. When increasing the tilt angle of the plates to 15°, it was observed that the tilt direction allowed for control over the direction of wave propagation. When the tilt angle was 15°, the largest proportion of transmitted waves reflected 1–2 times. When the plates were tilted at an angle of 30°, depending on the angle direction of the plates, most waves were reflected from 2 to 8 times. Meanwhile, when the panels were tilted at 45°, waves reflected from 4 to >10 times. With each reflection, the sound energy decreased depending on the absorption properties of the

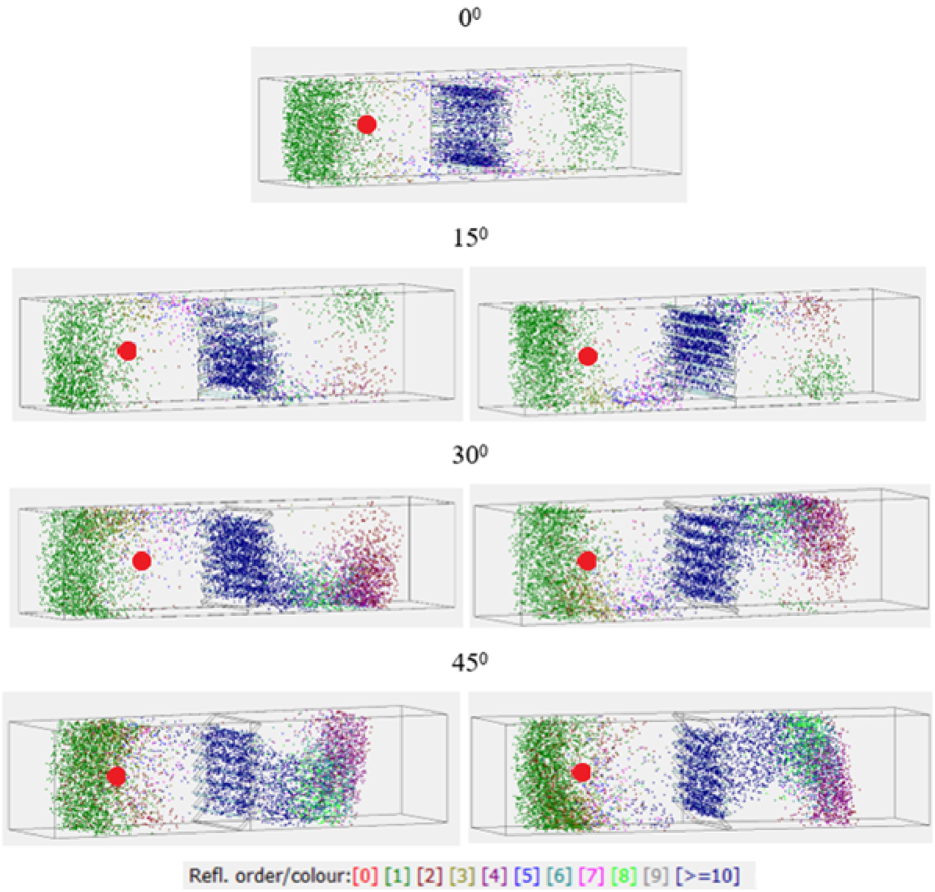

Fig. 7. Ray tracing of louvers, plates tilted at different angles.

material. The sound energy level on the other side of the louver was computed according to the following formula (ISO, 2010):

$$L_J = 10\log\left(\frac{J}{J_0}\right) \quad [\text{dB}], \tag{8}$$

where J is the sound energy, and J_0 is the reference sound energy level (10^{-12} J).

According to the aforementioned equation, reducing the energy level by two times results in sound level being reduced by approximately 3 dB. Similarly, in order to reduce the sound pressure level by 10 dB, the energy level must be reduced by 10 times. So, if at a certain frequency the sound wave loses 50 % of its energy, indicating a sound absorption of 0.5 for the rubber panel, then with each reflection the sound level can be reduced by 3 dB. This means that at the 10-th reflection, the sound level would be reduced by around 30 dB.

3.2. Sound absorption studies of rubber granule plates

Sound absorption was measured in a specially constructed device for the studies for material absorption – the impedance tube. Rubber panel samples, prepared according to the method described in Subsec. 2.3, were 30 mm in diameter and 12 mm in thickness. The composition of all the samples used in the studies is detailed in Table 1.

Table 1. Characteristics of rubber granulate panels.

Rubber granule panel	Particle size range [mm]	Rubber mass fraction [%]	Glue content [%]	Density [g/cm^3]
No. 1	4–15	94.9	5.1	0.601
No. 2	1–3	95.5	4.5	0.539
No. 3	1–15	95.7	4.3	0.666

Figure 8 shows the results of the sound absorption of rubber granule samples of compositions no. 1–3. The results indicate that the normal incidence sound absorption coefficient in the frequency band from 160 Hz to 630 Hz was approximately 0.1–0.15, due to relatively small sample thickness. However, from 800 Hz, the values of the normal incidence sound absorption coefficient started to rise and reached the maximum values of 0.79–0.96 at 3150 Hz. Notably, sample no. 2 had exhibited the highest normal incidence sound absorption coefficient (up to 0.96), consisting of 100 % devulcanized rubber granules. It was also observed that by reducing the amount of devulcanized rubber granules in

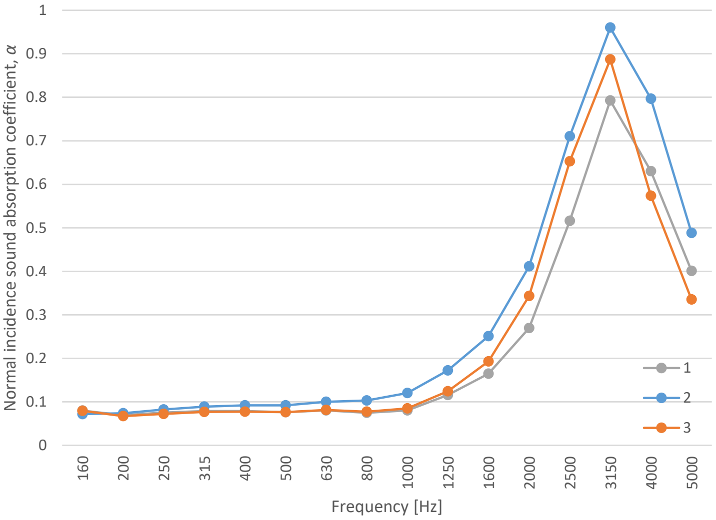

Fig. 8. Sound absorption results of rubber granule plates.

the composition, the normal incidence sound absorption coefficient decreased. Additionally, it was observed that the sound absorption of the rubber sample no. 3 reached up to 0.88, while the sound absorption of the rubber sample of composition no. 1 was 0.79. Based on the results, it can be stated that the panels made of 100 % devulcanized rubber granules had better sound absorption, as this type of panel exhibits the highest porosity. However, if the panel consists of rubber granules of a larger fraction, its porosity decreases, consequently leading to reduced sound-absorbing properties.

3.3. Research on the construction of acoustical louvers in a semi-anechoic chamber

Sound insertion loss studies of three structures with steel plates covered with different types of rubber granule panels were performed in a semi-anechoic chamber. Each structure was tested by tilting the louver plates from 0° to 45° in 15° steps. The plates were angled towards and away from the noise source (Fig. 9).

Tests conducted with constructions where plates were tilted towards the noise source revealed that at low frequencies ranging from 100 Hz to 500 Hz, the efficiency of all structures was similar. This similarity is attributed to low-frequency waves with wavelengths of 0.7 m to 3.3 m passing through the structure, creating resonances between the plates of the structure. However, due to the long wavelength, the louvers' construction had little attenuation of the sound pressure level. Since the width of the construction plates was 0.3 m, it was found that in all cases the critical frequency was determined at 1000 Hz. This depended on the thickness of the structure, since the wavelength of 1000 Hz was also close to 0.3 m. From 1000 Hz, the efficiency of structures began to increase rapidly, and in all cases reached its peak at 2000 Hz–3150 Hz.

At high frequencies, differences in the tilt angle of the plates became apparent. Our study showed that increasing the tilt angle of the plates also increased the insertion loss. Specifically, with the plates in 0° horizontal position, the sound level was reduced by 14 dB–17 dB at high frequencies. Changing the angle to 15° reduced the sound level by 17 dB–21 dB, while, further increasing the tilt angle to 30° and 45° resulted in sound pressure level reduction of 22 dB–26 dB and 24 dB–27 dB, respectively. The results showed that increasing tilt angle of louver plates by 15° increased sound reduction at high frequencies increased by an average of 2 dB–4 dB. It was also found that the efficiency also varied with different rubber granule plates. The best efficiency was obtained by using rubber granule plates no. 2, while the worst sound insulation properties was given by using rubber granule plates no. 1. The difference between plate no. 2 and plate no. 1 averaged 3 dB.

In the second case, where structures had plates tilted away from the noise source (Fig. 10), it was observed that at low frequencies ranging from 100 Hz to 500 Hz, the efficiency of all structures was similar because low-frequency sound waves with wavelengths of 0.7 m to 3.3 m, passed through the structure and generated resonances between the plates of the structure. As in the first case, critical frequencies were measured at 1000 Hz where the sound wavelength coincided with the width of the structure. The efficiency of the structures started to increase rapidly from 1000 Hz and reached its peak at high frequencies between 2500 Hz and 3150 Hz.

At high frequencies, differences in the tilt angle of the plates became apparent. It was observed that increasing the angle of the construction plates increased insertion loss. Specifically, with the plates in 0° horizontal position, the sound level was reduced by

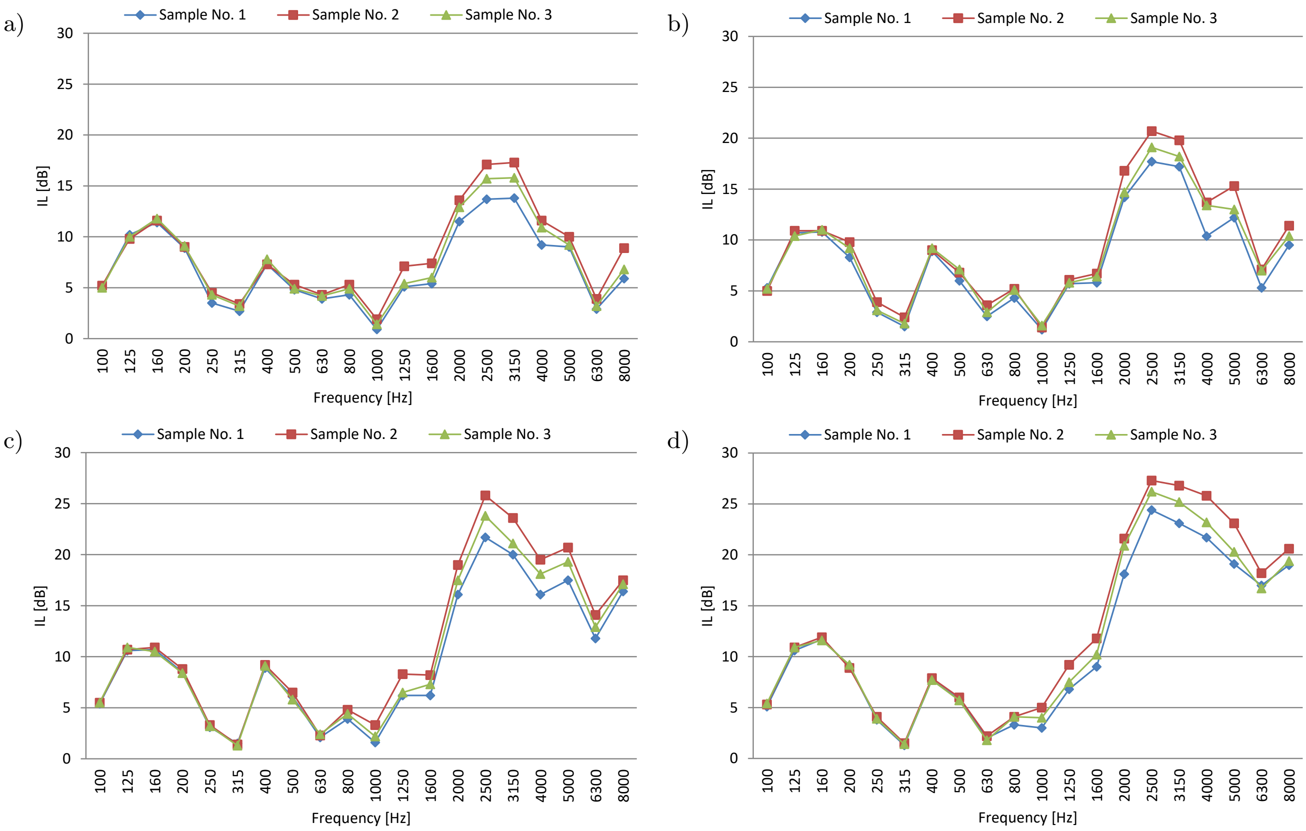

Fig. 9. Results of the insertion loss of the louvers with different angles of the plates tilting towards the source: a) 0°; b) 15°; c) 30°; d) 45°.

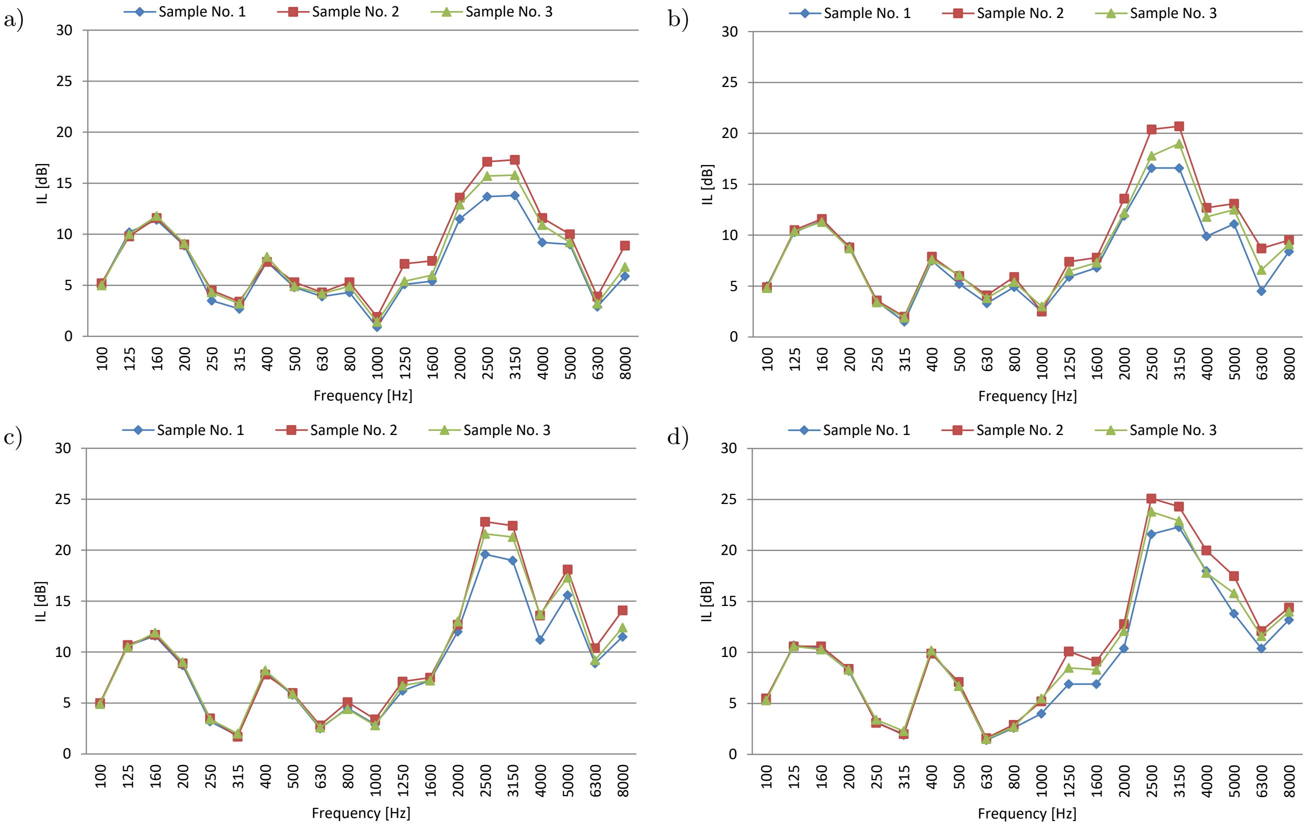

Fig. 10. Results of louvers' insertion loss with different tilt angles of plates away from the source: a) 0°; b) 15°; c) 30°; d) 45°.

Table 2. Equivalent reduction of the sound pressure level L_{Aeq} [dB].

Louvers plate tilt angle	Equivalent reduction of the sound pressure level L_{Aeq} [dB]		
	Plates covered with rubber granulate no. 1	Plates covered with rubber granulate no. 2	Plates covered with rubber granulate no. 3
0°	6.9	9.4	8.2
15° towards the source	8.4	10.5	9.6
30° towards the source	9.3	12.2	11.7
45° towards the source	9.9	13.5	11.9
15° away from the source	7.7	10.5	9.3
30° away from the source	8.8	12.2	11.0
45° away from the source	9.2	12.9	11.8

14 dB–17 dB at high frequencies. Increasing the angle to 15° resulted in insertion loss values ranging from 16 dB to 21 dB at 2500 Hz. Further changing the tilt angle to the 30° led to sound pressure level reduction by 20 dB–24 dB, while, at an angle of 45°, the sound pressure level was reduced by 22 dB–25 dB. As in the first case, increasing the angle by 15° steps resulted in sound pressure level reduced by an average of 2 dB–3 dB. The dependences on the rubber granulate panels were also determined during the research. Our study showed that acoustic louvers covered with rubber granulate plate no. 2 exhibited a 2 dB greater reduction in sound pressure level compared to those in plate no. 3, and up to 6 dB better reduction compared to those using rubber granule panel no. 1.

In the study, it was also important to determine the equivalent decrease in the sound pressure level, which is given in Table 2.

The results of the equivalent sound reduction showed the same trends. The research results showed that the best reduction in sound pressure level occurred when the tilt angle of the plates was 45°. The increase in angle was found to improve the results by 0.5 dB to 1 dB. In addition, the best results were obtained by covering the construction plates with no. 2 rubber granule panel. When comparing different rubber granule plates, variations in results were noted, with differences of up to 2 dB.

4. Discussion

The innovative design of the louver construction was based on the principle of sound absorption. According to ray-tracing simulation data, it was found that by changing the angle of the plates, sound waves could be reflected up to 10 times. Sound wave theory states that with each reflection, the sound wave loses some of its energy. To increase the efficiency of acoustic louvers, the plates were covered with sound-absorbing materials. Since such constructions were used under rather difficult conditions, in the presence of high heat, humidity, etc., it is especially important to select the right materials. One of the best solutions to implement the principles of circular economy is to recycle and reuse waste tire rubber. In the studies, waste tires were shredded into two different fractions, with a particle size of 1 mm–3 mm and 4 mm–15 mm, respectively. To further increase porosity, rubber granules were devulcanized. Three type of rubber granule plates were created. The normal incidence sound absorption coefficient of no. 1 rubber granule plate reached 0.79, no. 2 – 0.96, and no. 3 – 0.88 at 3150 Hz.

The results of the research showed that the best sound absorption values were achieved at 3150 Hz, whereas at low frequencies (160 Hz–630 Hz) the absorption reached 0.1–0.15. Similar trends were seen in the insertion loss study. The sound reduction of louvers began to increase from 1000 Hz, along with increasing sound absorption, From this frequency, the insertion loss values reached 15 dB–25 dB according to the angle of louver plates. The sound insulation began to decrease from 3150 Hz, which was also compared to the sound absorption results. Therefore, in summation of the results, it was found that there was a direct relationship between the sound insulation efficiency of the acoustic louvers and the absorption properties of the material since the best results were obtained using rubber granule panels with the highest sound absorption. Also, the change in angle of the louver plates increased the number of reflections of sound waves. When construction plates are in the 45° position, the number of reflections can reach up to 10 times, which means that with each reflection, more than half of the energy, depending on material sound absorption, could be absorbed. The theory states, that if at a certain frequency the sound wave loses 50 % of its energy, then with each reflection, the sound level can be reduced by 3 dB, which means that at the 10th reflection, the sound level is reduced by around 30 dB and this compares with the results of the insertion loss. The highest values reached 25 dB at 2500 Hz–3150 Hz.

According to the literature, in general, all acoustic louvers provide about 10 dB–12 dB of sound insulation. In our case, a structure with 45° angled plates achieved up to 11.9 dB of equivalent reduction of the sound pressure level. So, it can be stated that the use of materials made of used tires can provide a good sound-insulating structure for equipment that needs to ensure good air circulation.

5. Conclusions

The study has shown that at frequencies from 100 Hz to 315 Hz, all materials uniformly reduced the sound level, even by changing the tilt angle of the plates at different angles. Particularly, at 125 Hz–160 Hz, a greater decrease in sound level was found to be 11 dB–12 dB. At 200 Hz–315 Hz, the insertion loss dropped to 3 dB.

At frequencies from 400 Hz to 1250 Hz, all materials also similarly reduced noise, regardless of the changing tilt angle of the plates. In this frequency band, the decrease in sound level reached the lower limits. At 630 Hz–1000 Hz, the reduction in sound level was only 1 dB.

Differences in the reduction of sound level occurred only at high frequencies, where the best efficiency of the louvers was determined. The best efficiency was found to be achieved at frequencies of 2500 Hz–3150 Hz, where, depending on the angle and the material used, the reduction in sound level reached 14 dB–27 dB.

The study has shown that changing the angle of the louvers plates in 15° increments increases sound insertion loss by 2 dB–4 dB with all materials at each increment.

In addition, the best level of sound reduction was achieved with acoustic louvers whose plates were covered with rubber panel no. 2, made of chemically treated rubber granules of 1 mm–3 mm in size. The louver, which was covered with rubber panels no. 1 (granule size 4 mm–15 mm), produced 3 dB–4 dB lower sound level reduction than the panels no. 2. Construction with plates covered with rubber granule plate no. 3, which was made by mixing both types of granules, yielded sound level reduction on average 2 dB better than the structure covered with a rubber panel of mechanically processed rubber granules, but on average 2 dB worse than the structure covered with a board of chemically processed granules.

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