Archives of Acoustics Online First August 6, 2025 https://doi.org/10.24425/aoa.2025.154817

Research Paper

Comparative Study of the Acoustic Efficiency of Prototype Sound Absorbing Panels Used in the Railway Track

Grzegorz KLEKOT[(1)], Mariusz WĄDOŁOWSKI[(1)*], Cezary KRAŚKIEWICZ[(2)], Artur ZBICIAK[(2)]

[(1)] *Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology*
Warsaw, Poland

[(2)] *Faculty of Civil Engineering, Warsaw University of Technology*
Warsaw, Poland

*Corresponding Author e-mail: mariusz.wadolowski@pw.edu.pl

Received November 28, 2024; revised March 2, 2025; accepted June 25, 2025; published online August 6, 2025.

The article presents the results of comparative studies concerning the efficiency of systems aimed at minimising the acoustic nuisance of noise generated by the railway vehicle movement. The issue of noise in railway traffic is a significant challenge, affecting both human health and the quality of life in the vicinity of railway lines. Prototype sound absorbing panels with varied surface geometry, a rubber slab, and ballast layer (stone aggregate, grain size 31.5/50 mm) were examined. Experiments were conducted in a reverberation chamber, analysing the response to broadband noise excitation. The reverberation chamber allows for obtaining repeatable results, eliminating the influence of external sound sources. It enables the assessment of the sound absorption properties of various materials which makes it possible to determine their effectiveness in noise reduction. The research methodology included measurements of reverberation time in different frequency bands for an empty chamber and a chamber containing the tested materials. The obtained differences in reverberation times provide information on the influence of the tested material on the distribution of acoustic energy in individual frequency bands. The research results allow for a preliminary assessment of the effectiveness of the tested materials in the task of reducing railway line noise.

Keywords: railway traffic noise; noise reduction; acoustic insulation; sound-absorbing materials; vibration damping; reverberation chamber.

1. Introduction

Currently, transport is a fundamental element of the global economy, serving as a key factor enabling the worldwide flow of goods and services. Modern producers and consumers prefer just-in-time delivery instead of stockpiling, which allows for the reduction of storage costs and increases the efficiency of logistic processes. This requires transport to be reliable, punctual, and economically justified. Rail transport plays a significant role in the implementation of both freight and passenger transport over medium and long distances. The dynamic development of high-speed rail positions it as a serious competitor to air transport over medium distances. The main advantages of rail transport include high load capacity, reliability, low accident rates, and minimal sensitivity to changing weather conditions. However, one of the key challenges remains the problem of noise emission, which negatively affects the natural environment and human health. Railway noise can lead to chronic stress, sleep disturbances, and prolonged exposure to high noise levels may increase the risk of hypertension and other cardiovascular problems (Basner *et al.*, 2014; Münzel *et al.*, 2017). Moreover, railway noise adversely affects fauna, disrupting the natural behavioural patterns of animals and contributing to a decrease in biological diversity in areas adjacent to railway lines.

Studies conducted in Europe have shown that noise generated by rail transport is one of the most burdensome sources of transport noise (Licitra *et al.*, 2016; Zhang *et al.*, 2019). These studies were based on measurements of noise levels at various locations along railway lines and on the analysis of the impact of this noise on residents of neighbouring areas. Both field data and surveys on people's perception of noise nuisance were used, which allowed for a comprehensive assessment of its impact.

In response to this problem, legal regulations have been developed to determine acceptable noise levels for different categories of areas. Depending on their purpose, these areas have been classified into four groups: spa areas (places of particular health significance, requiring the highest level of acoustic protection), single-family residential areas (characterised by low population density, where a moderate noise level is required), multi-family residential areas (with higher building density, requiring more flexible acoustic norms), and urban areas (areas with high traffic intensity, where due to the nature of activities, higher noise levels are acceptable). The maximum permissible noise level for spa areas is 50 dB(A), while in urban areas, this value is 68 dB(A).

Therefore, the aim of this article is to conduct a comparative study of prototype sound-absorbing element-rubber slabs, ballast layers, and specially contoured concrete panels, and to assess their effectiveness in reducing railway noise. The novelty of our approach lies in applying an uncommon, yet straightforward measurement method based on the difference in reverberation time (RT30). By comparing how each material influences RT30 under identical test conditions, we can rapidly evaluate and contrast their noise-attenuating properties. This direct and simple use of reverberation-time differences is rarely encountered in railway noise analyses, making our study particularly valuable for future track design. In this way, we offer new insights into how material selection and surface geometry can be optimized to meet modern standards of acoustic performance.

2. Sources of noise and its propagation

When analysing the problem of reducing noise generated by railway traffic, various factors affecting its level must be considered (Cao *et al.*, 2018). The most important factors include train speed, the design of locomotives and carriages, the type and condition of the track, the insulating materials used, and atmospheric conditions. Aerodynamic noise becomes the dominant source at train speeds above 250 km/h because, as speed increases, the airflow around the train generates a significant amount of turbulence, leading to more intensive generation of sound waves. The design of the locomotive's front, the carriage connections and the speed of travel contributed to its creation. Another significant source of noise is the locomotive's drive system. The main noise generating components include traction motors, gearboxes (Andrés *et al.*, 2021), and cooling systems. Noise levels can be reduced by using sound-absorbing shields, optimising gearbox design, and modernising cooling systems to operate more quietly and efficiently. Sound-reducing shields include rubber mats and mineral fibre panels. According to (Leštinský, Zvolenský, 2019), optimising the design of carriage bogies and braking systems can reduce noise levels by up to 15 dB. Modernisation of railway infrastructure, including rail grinding and the installation of vibration dampers, also contributes to reducing noise emissions (Zvolenský *et al.*, 2017). Vibration dampers are devices mounted on rails that help reduce rail vibrations. They absorb vibration energy, limiting its transmission to other parts of the track and the surroundings, consequently reducing generated noise. Kraśkiewicz *et al.* (2024) investigated possible applications of rubber granulate SBR (styrene-butadiene rubber) produced from recycled waste tires as an elastic cover for prototype rail dampers. The authors performed laboratory tests, with a focus on their operational durability. Rail grinding removes surface irregularities, which lowers the generation of vibrations and wheel-rail friction, ultimately reducing the level of generated noise.

3. Noise reduction

There are many methods of reducing noise associated with railway traffic, which are based on changes in track construction, track geometry, and the materials used. An example of an effective method is the use of elastic track pads, which reduce vibrations transmitted through the tracks and thus reduce noise. Elastic track pads have been successfully implemented in projects in Germany and Switzerland (Němec *et al.*, 2020), where their implementation contributed to a significant improvement in acoustic comfort in urban areas. Elastic track pads are made of materials such as polyurethane or rubber mixtures, which provide appropriate elasticity, enabling effective vibration damping.

In the case of new railway lines, significant noise reduction, even up to 25 dB, can be achieved by building earth embankments on both sides of the tracks (Bunn, Zannin, 2016). However, constructing such embankments involves high costs and the need for a large amount of space, which may limit their use in densely built-up areas. Additionally, embankments require appropriate land development, which is not always possible in cities and urban areas. These embankments act as natural sound barriers, absorbing and dispersing sound waves, reducing their propagation towards the surroundings. However, such infrastructure requires a significant amount of space, which often limits its application in urban areas (Sun et al., 2019; 2020). In such cases, alternatives can be smaller acoustic barriers, green walls, or sound-absorbing screens, which can be more easily adapted to urban conditions. Examples of materials used in sound-absorbing screens include mineral fibre panels, concrete-rubber composites, and acrylic glass, which effectively reflect and disperse sound waves, limiting their propagation. An alternative approach involving trackbed sound absorptive panels for reducing wayside noise on slab track was examined by Glickman et al. (2011), who discuss both the benefits and practical considerations of using porous concrete elements in lieu of conventional ballasted track. There are also examples of combining multiple complementary track-related solutions, such as sound-absorbing panels, low acoustic barriers, and rail dampers. For instance, a study conducted on an LRT line in Athens (Vogiatzis, Vanhonacker, 2016) demonstrated that the simultaneous use of absorbing panels, low barriers, and rail dampers resulted in noise reduction reaching of up to 10 dB(A), significantly surpassing the initial goal of 6 dB(A). This 'multi-pronged' approach serves as an inspiring example for projects carried out in urban areas, where minimizing noise levels as much as possible is crucial while maintaining minimal interference with existing infrastructure.

4. Experimental study

The research was conducted to assess the effectiveness of prototype subgrade elements in reducing the acoustic nuisance of railway lines. Understanding the sound-absorbing properties of various structures is crucial for optimising noise reduction in railway infrastructure.

A reverberation chamber was used for the study, which allows for easy comparison of sound absorption by different materials and structural elements (Castiñeira-Ibáñez et al., 2012). The diffuse, homogeneous acoustic field in the reverberation chamber enables repeatable results, leading to reliable comparisons in the assessment of materials (Szczepański et al., 2023) and elements shaping the acoustic properties of the environment. The reverberation chamber eliminates the influence of external factors (reflections of sound waves from random objects, uncontrolled noise sources, etc.), allowing for repeatable measurement of the reverberation time RT30. The experimental setup enabled comparisons in the frequency domain (in 1/3 octave bands).

In the presented study, all tested samples occupied the same surface area 1.5 m × 1.3 m on the floor of the reverberation chamber, ensuring comparability of measurement results. Despite differences in shapes and materials (e.g., trapezoidal grooves, half-round grooves, rubber slabs, or ballast layers), each sample was arranged to cover an identical area. This approach allows us to focus on the intrinsic acoustic properties of each tested variant without bias due to uneven surface coverage. Consequently, we did not introduce detailed external references in this section, concentrating instead on our own measurement protocol. By measuring the RT30 in 1/3 octave bands for each sample and comparing it with the empty chamber baseline, we isolated the influence of material and geometry on sound absorption and dispersion, rather than variations in the sample size.

The tested sound absorbing panels (Fig. 1) were made of porous concrete, whose recipe was marked with the symbol '220/10' – number '220' refers to the volume of cement grout (220 dm^3), and number '10' indicates the percentage of sand in the crumb pile. The concrete recipe was elaborated within laboratory tests, and the surface grooving was designed using numerical simulations. All tested elements were produced in the laboratory of the Faculty of Civil Engineering at the Warsaw University of Technology (Kraśkiewicz et al., 2024). A recent study by Zhao et al. (2014) likewise confirmed that porous sound-absorbing concrete slabs can effectively reduce railway noise by up to 4 dB at speeds around 200 km/h, highlighting the importance of careful aggregate gradation and fibber content selection. A similar approach to optimizing the mix design of porous, sound-absorbing blocks in urban train tunnels was proposed by Lee et al. (2016), emphasizing the role of lightweight aggregates and structural requirements for efficient noise mitigation.

Fig. 1. Sound absorbing panels with dimensions 500 mm × 500 mm × 100 mm.

Two types of panels, stone aggregate, and panel rubber were considered:

- panel 1 – porous concrete panels with trapezoidal grooves: 500 mm × 500 mm × 100 mm (Fig. 2);
- panel 2 – porous concrete panels with half-round grooves: 500 mm × 500 mm × 100 mm (Fig. 3);
- rubber: 1500 mm × 1300 mm × 150 mm (Fig. 4);
- ballast layer of 31.5/50 mm stone aggregate (track bed), covering an area of 1500 mm × 1300 mm × 150 mm (Fig. 5).

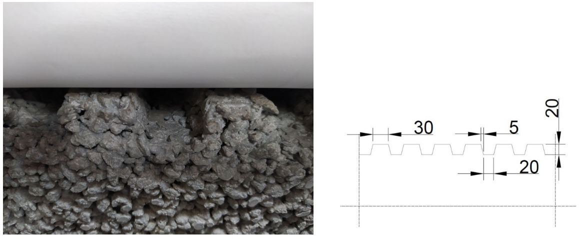

Fig. 2. Panels type 1 (trapezoidal grooves).

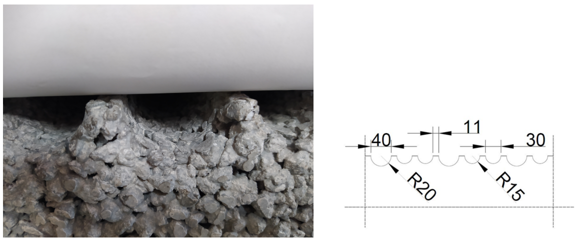

Fig. 3. Panels type 2 (half-round grooves).

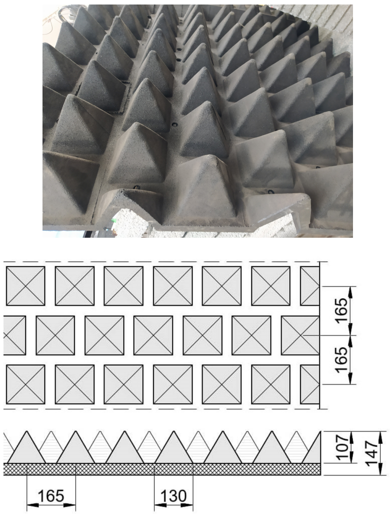

Fig. 4. Rubber panel.

Fig. 5. Ballast layer (stone aggregate, grain size 31.5/50 mm).

Concrete slabs (sound absorbing panels) are characterised by high mass and stiffness, allowing them to effectively reduce vibrations and absorb acoustic energy. Rubber panels exhibit excellent sound-damping properties due to their elasticity, which enables the absorption of acoustic waves. Stone aggregate, owing to its varied shapes and porosity, can effectively scatter and dampen sound waves. The selection of these elements is due to their wide applicability in railway track constructions and potential acoustic benefits. Concrete panels have a high mass, which can influence vibration reduction, rubber panels have sound-absorbing properties, and stone aggregate is commonly used in tracks due to its ability to dampen vibrations (Fediuk *et al.*, 2021; Shahidan *et al.*, 2017).

All measurements were conducted in the reverberation chamber; the reverberation time RT30 of the chamber with the tested samples was measured. Measuring and analytical equipment from Brüel & Kjær was used, consisting of an analyser and PULSE LabShop software. The chamber with the tested elements, the sound source, and the measurement microphones are shown in Fig. 6.

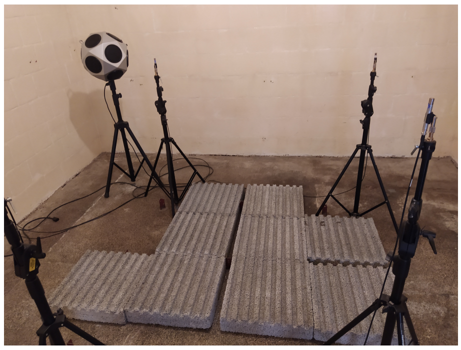

Fig. 6. Test setup in the reverberation chamber.

The test acoustic signal was generated by a white noise generator using B&K LabShop software, specifically the 'Reverberation Time' application, with an omnidirectional sound source BK 4292. White noise is characterised by a uniform distribution of energy across all frequency bands, allowing for a relatively comprehensive assessment of the acoustic properties of materials. The omnidirectional sound source enables even distribution of sound waves in the chamber, ensuring repeatable measurement results. Four BK 4189 microphones, arranged inside the chamber, recorded changes in acoustic pressure. The reverberation time was measured in standardised $^1/_3$ octave bands for random noise (so-called white noise) in the range from 50 Hz to 8 kHz. Changes in acoustic pressure were observed after switching off the sound source, and based on this, the RT30 was determined. The difference between the reverberation time of the empty reverberation chamber and the chamber with samples illustrates the effectiveness of the tested system, allowing for the assessment of how well a given material can absorb acoustic energy. A reduction in reverberation time indicates better sound-absorbing properties of the tested material. During the experiments, three series of five measurements were carried out with different positions of the sound source (the locations of the microphones and the sound source are schematically presented in Fig. 7). Each microphone recorded 11-second time histories. Based on them, reverberation times in 1/3 octave bands were averaged. Then, the results for all series were averaged. Measurement results are presented in the form of the third-octave spectrum of the average reverberation time and the difference between the reverberation time for the empty chamber and with samples.

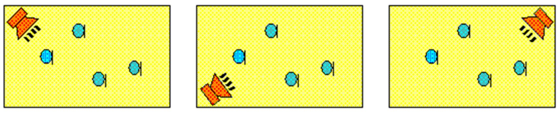

Fig. 7. Schematic of the measurement setup.

Third-octave spectra (1/3 octave bands) were obtained using the BK Connect analysis software. This research method allows for comparing the sound absorption by individual sound-absorbing structures.

The RT30 is determined based on a drop in the sound level of 30 dB. This parameter is primarily used in analyses of room acoustic properties (e.g., concert halls, recording studios, cinemas, etc.); nevertheless, the described methodology also allows for inferring the suitability of subgrade elements for reducing railway line noise.

5. Measurement results

The research results indicate that the differences in reverberation time between the empty chamber and the chamber with the tested samples provide significant information about the acoustic effectiveness of the materials tested. Figure 8 presents the reverberation time values measured in the empty reverberation chamber in third-octave bands. The longest reverberation time, approximately 4 s, was observed for the band with a centre frequency of 630 Hz.

Then, the reverberation times of the chamber in which the tested materials were placed were measured and the difference in reverberation time between the empty chamber and the chamber filled with the samples was calculated; the greater the ability of the tested material to absorb sound, the greater the difference. Which is crucial for applications in the context of railway infrastructure. These results can be used to optimise the selection of construction materials for more effective noise minimisation. Figure 14 presents a summary of the measurements.

The measurements were performed for the following types of samples: detailed measurement results are presented in Figs. 9–13. The graphs contain the reverberation time measured in the chamber with the tested samples and the path and graph of the calculated time difference between the empty chamber and the chamber with the samples.

The rubber panel were the most effective in attenuating sounds at low and medium frequencies (Fig. 14). The difference in reverberation time in the chamber with such panels for bands 125 Hz–400 Hz was up to 1 s. Concrete sound absorbing panels with specific surface configurations reduced the reverberation time to 1.9 s for frequency ranges 400 Hz–2000 Hz. Stone aggregate

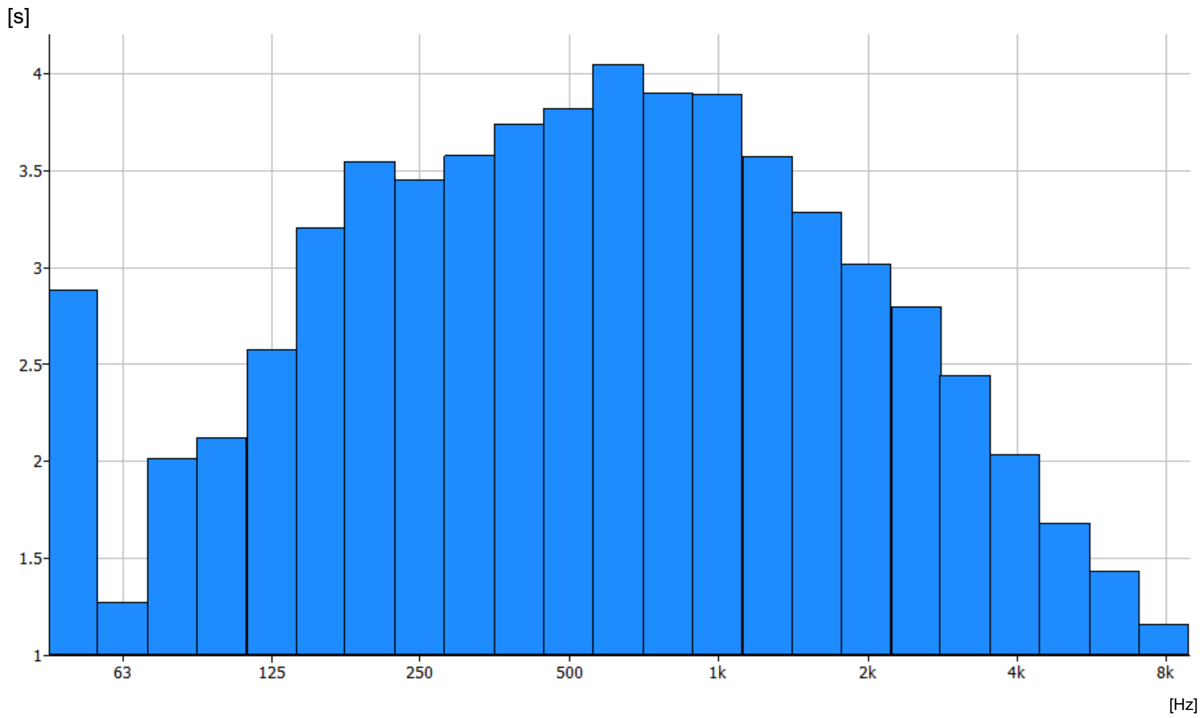

Fig. 8. Reverberation time of the empty chamber.

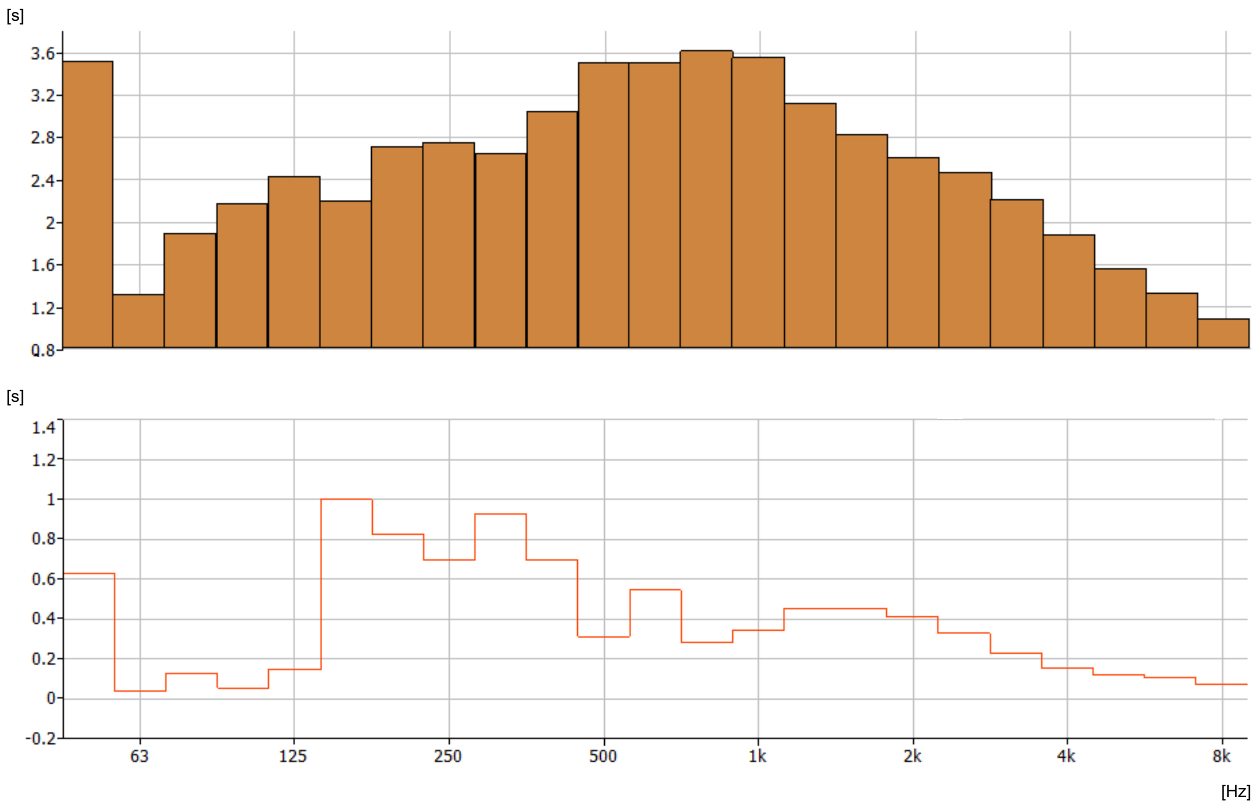

Fig. 9. Reverberation time – rubber, sample 1 (top); differences in reverberation time between an empty chamber and a chamber with tested samples (bottom).

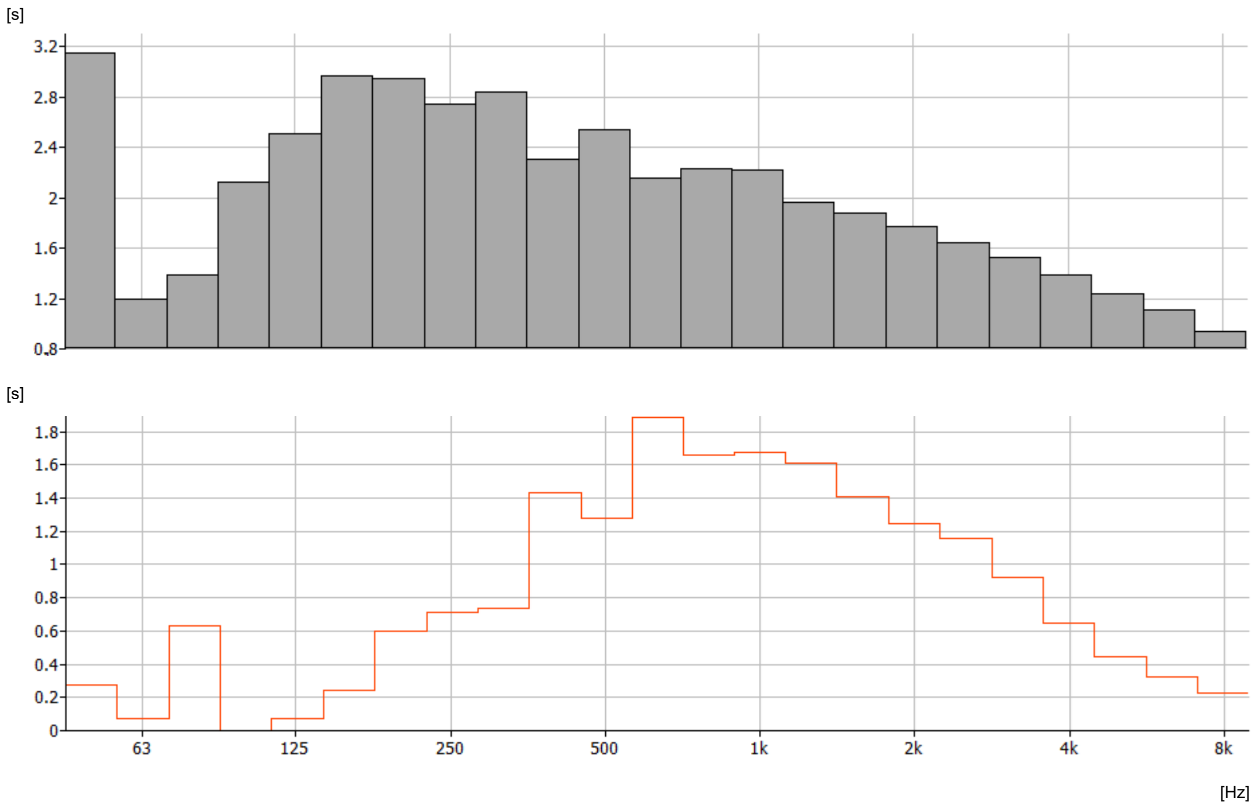

Fig. 10. Reverberation time – panel type 1, sample 2 (top); differences between an empty chamber and a chamber with tested samples (bottom).

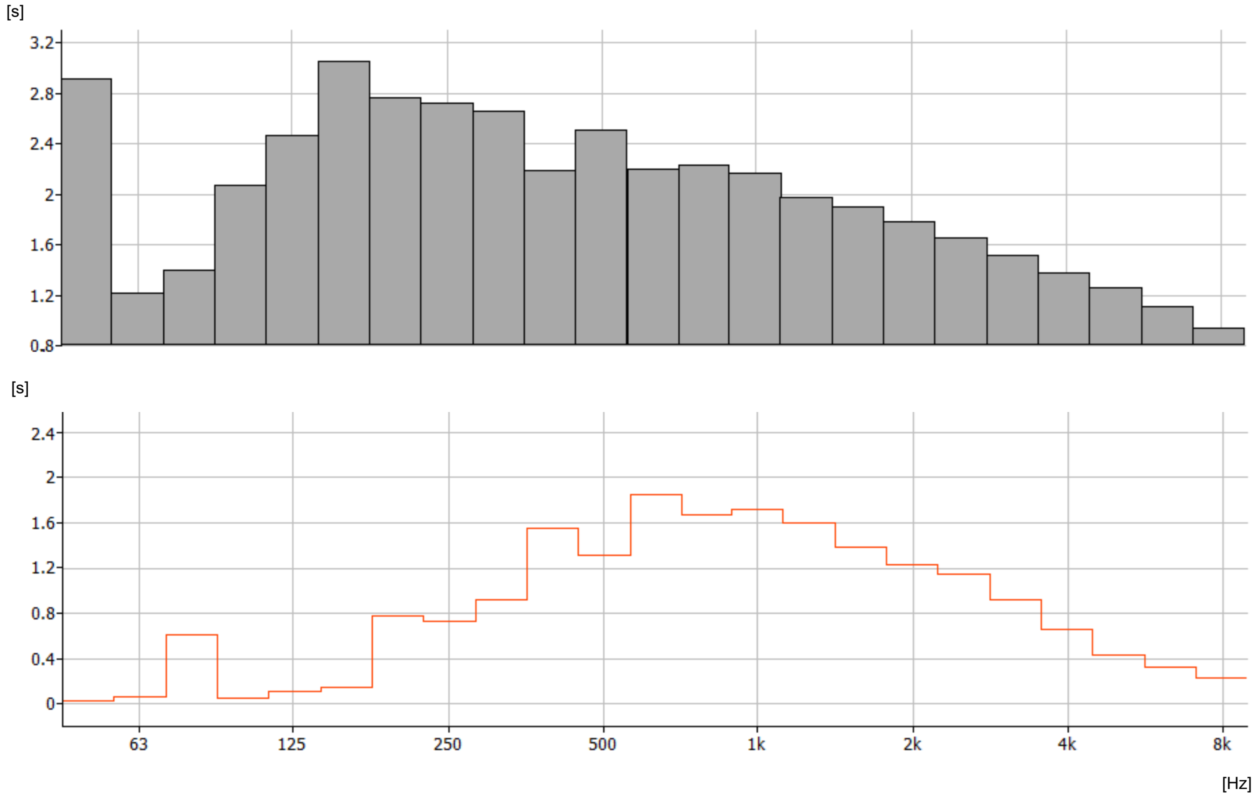

Fig. 11. Reverberation time – panels type 1 and 2, sample 3 (top); differences between an empty chamber and a chamber with tested samples (bottom).

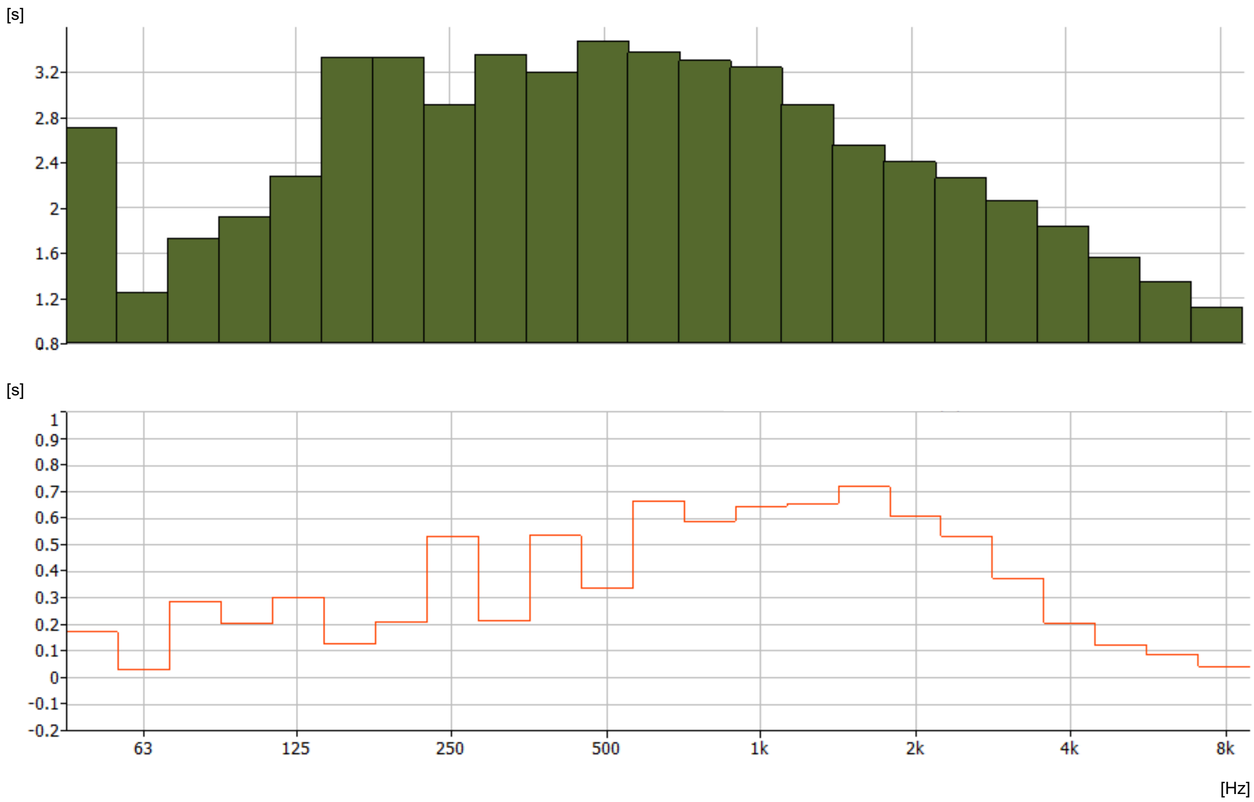

Fig. 12. Reverberation time – stone aggregate, sample 4 (top); differences between an empty chamber and a chamber with tested samples (bottom).

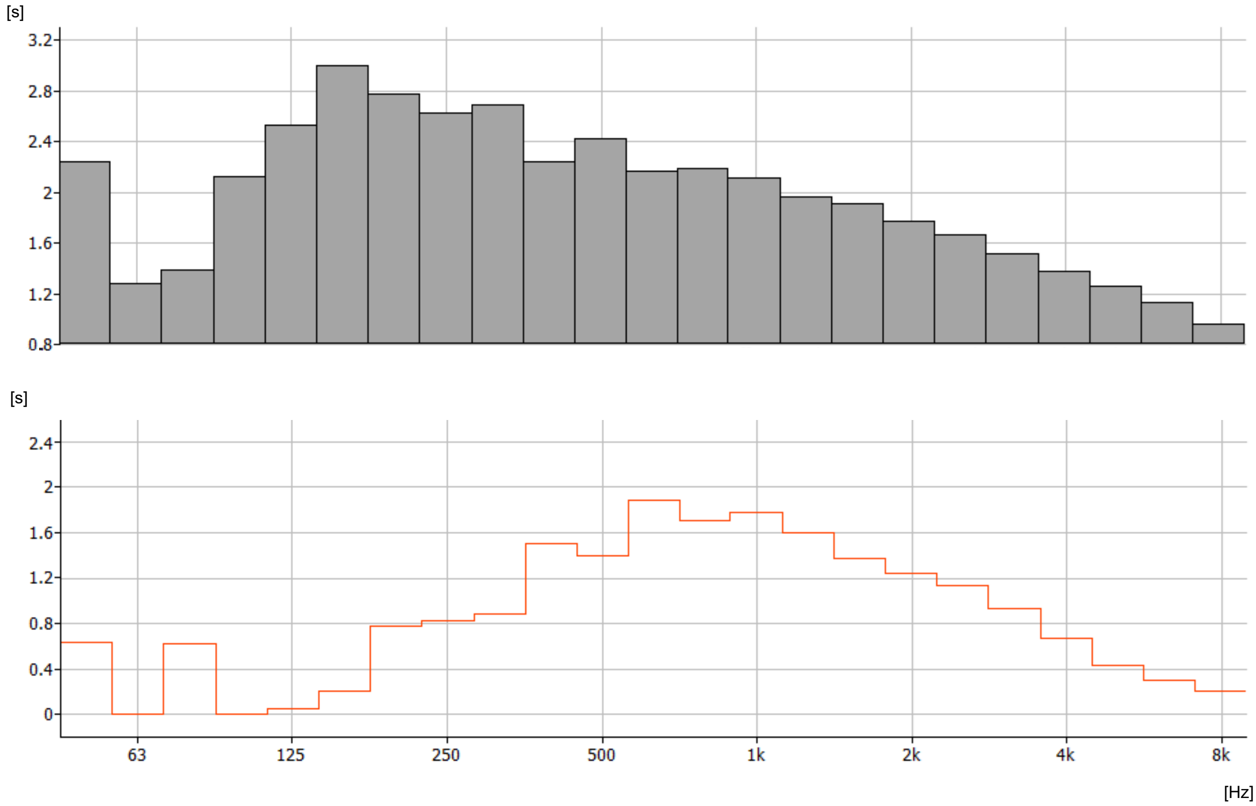

Fig. 13. Reverberation time – panel type 2, sample 5 (top); differences between an empty chamber and a chamber with tested samples (bottom).

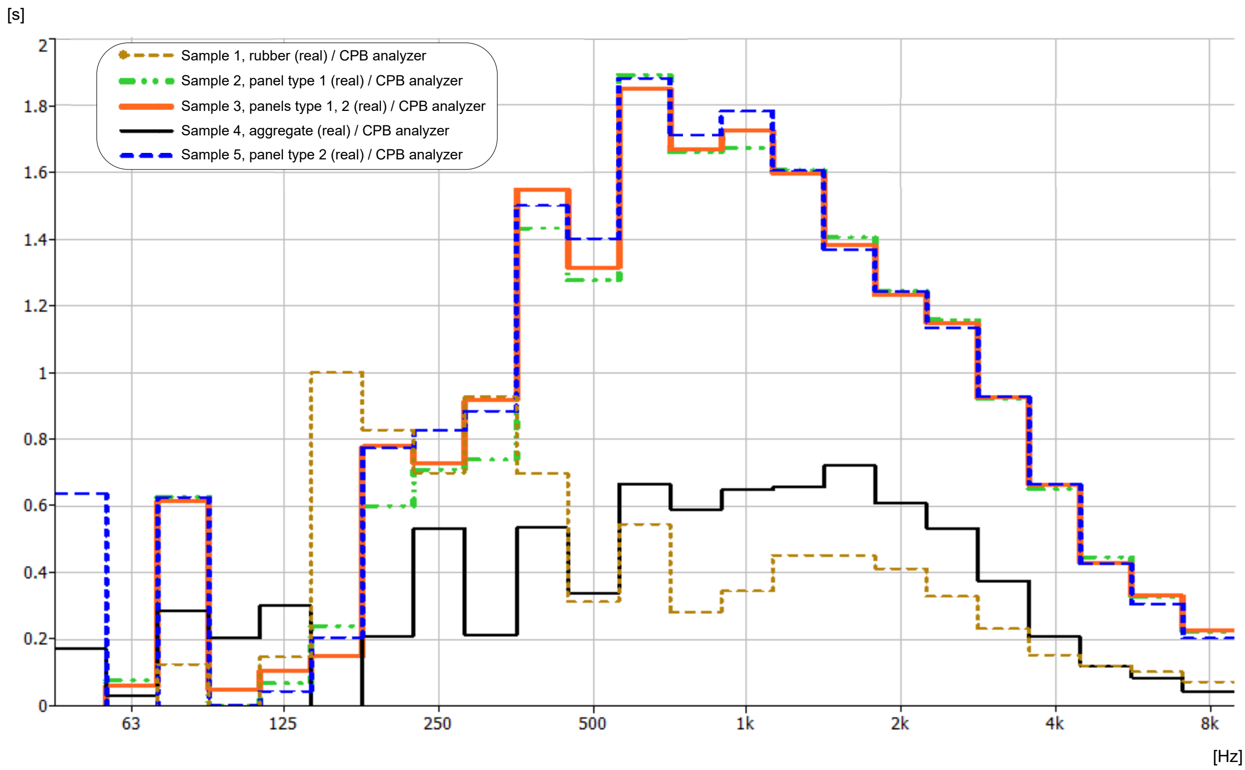

Fig. 14. Differences in reverberation time between an empty chamber and a chamber with tested samples in 1/3 octave bands.

caused an average decrease in reverberation time of about 0.5 s across a wide band of tested frequencies.

The obtained results indicate that rubber panels were particularly effective in attenuating sounds in low and medium frequencies, while concrete panels are more effective in higher ranges. This analysis suggests that combining both materials could yield even better results, providing effective noise reduction over a wider frequency range. Combining these two materials may be particularly beneficial in applications where effective noise reduction is required under various acoustic conditions – for example, in places with high railway traffic intensity, where it is important to limit both low and high components of noise. For instance, railway stations located in residential areas could significantly benefit from such a solution, minimising both low-frequency vibrations and sharp high-frequency sounds generated by passing trains.

Although rubber panels demonstrated high sound attenuation in crucial frequency bands for human hearing, one must note that rubber-based solutions can be more costly compared to concrete or aggregate-based panels. Additionally, rubber may pose certain challenges in tunnel applications due to stricter fire safety regulations and limited heat resistance. Consequently, the decision to implement such materials must balance acoustic performance, economic feasibility, and safety requirements. For instance, in designing 'quiet' railway tunnels, where controlling reverberation is paramount, one might favour materials that effectively disperse acoustic waves while meeting fire protection standards. This highlights why alternative solutions – such as specifically shaped concrete panels or hybrid systems using aggregate – also deserve further investigation. They can offer a balanced compromise between acoustic efficiency, structural constraints, and compliance with tunnel safety regulations.

It is also crucial to note that noise reduction depends not only on the absorption of acoustic waves but equally on their dispersion. Materials with specific surface geometries can scatter energy effectively, reducing the perceptible noise level. In enclosed spaces such as tunnels, where sound reflections are intensified, geometry-induced dispersion can be as significant as direct absorption. Therefore, further research on various panel shapes (e.g., trapezoidal grooves, half-round hollows, or more complex fractal patterns) may provide solutions that combine high dispersion capacity with practical considerations such as fire safety or cost-effectiveness.

When selecting materials for full-scale application, economic factors play a vital role. Rubber-based solutions, although acoustically effective, can be more expensive to install and maintain than concrete panels. Additionally, their long-term durability in harsh conditions (e.g., high temperatures, tunnels) may raise further concerns. Hence, research aimed at balancing performance, cost, and safety is necessary before deciding on the large-scale implementation of any chosen material.

6. Discussion

The results presented in the previous section indicate that rubber-based panels provided the highest level of sound attenuation in the low- and mid-frequency ranges, while the specially shaped concrete panels performed better in higher frequency bands. The ballast layer (stone aggregate), in turn, showed moderate effectiveness across a broad range of frequencies, though not as pronounced as rubber's performance in the low-mid domain.

From a practical standpoint, it is crucial to balance acoustic performance with cost, durability, and safety. Despite its strong noise reduction properties, rubber can be more expensive to produce and maintain and may pose challenges in high-temperature or fire-critical environments (e.g., tunnels). On the other hand, properly contoured concrete panels can effectively disperse acoustic waves and are often simpler to adapt to fire protection standards. The aggregate-based layer remains a standard solution in conventional track structures and can be further optimized by tailoring its geometry or combining it with other materials.

A key insight emerging from these tests is the importance of surface geometry in scattering acoustic energy. In enclosed spaces, such as railway tunnels, geometry-driven dispersion can be as significant as the direct absorption. Future efforts could therefore investigate hybrid solutions blending different materials with complementary frequency attenuation strengths, while also meeting cost and safety requirements.

Moreover, numerical simulations (for instance, the finite element method (FEM) analyses) could complement the experimental approach, allowing for refinement of material selection and panel geometry without the need for large-scale prototypes. Although the present study focused on a straightforward methodology based on reverberation time differences (RT30), integrating empirical data with simulation results may provide a more comprehensive foundation for designing next generation 'quiet' railway structures.

7. Conclusion

The conducted comparative studies in the reverberation chamber allowed for the analysis of the acoustic efficiency of various materials for use in railway infrastructure. The results of these studies may contribute to increasing acoustic comfort in the vicinity of tracks and support the optimisation of sleeper designs and other track elements. Identifying the most effective noise-damping materials is fundamentally important for reducing the acoustic nuisance generated by railway traffic.

The use of a reverberation chamber and the measurement of the difference in reverberation time between the empty chamber and the chamber with samples constitutes an innovative and practical approach, especially in the context of research on new noise-damping materials. This allows for obtaining precise and repeatable results that are independent of variable external conditions. This approach enables the accurate determination of how effectively materials absorb sounds in different frequency bands. Consequently, researchers can better understand which materials have the greatest potential for practical application in terms of acoustic efficiency. Let us also note a certain convergence of conclusions from the studies conducted in the reverberation chamber and the previously presented results of the bench experiment (Kraśkiewicz *et al.*, 2024).

Further research could include a long-term assessment of the durability of the tested materials, particularly regarding their resistance to atmospheric factors and mechanical wear. Undoubtedly, it is necessary to analyse the implementation costs of individual materials in actual infrastructure projects and assess their impact on the total maintenance costs of tracks. Such data would be invaluable when making decisions by designers and managers of railway infrastructure.

As an additional step in future research, numerical methods (such as FEM) could be employed to complement the experimental findings. However, these analyses exceed the scope of the current study.

Funding

The research presented in the publication was carried out as part of the project 'Innovative solutions of people and the environment protection against rail traffic noise'. The project is co-financed by the European Union from the European Regional Development Fund under the Smart Growth Operational Programme and by PKP PLK S.A. within the framework of the BRIK.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' contribution

Grzegorz Klekot and Cezary Kraśkiewicz conceptualized the study; Mariusz Wądołowski wrote the original draft; Mariusz Wądołowski and Artur Zbiciak performed the analysis. All authors contributed to the interpretation of the data and reviewed and approved the final version of the manuscript.

References

1. Andrés V.T., Martínez-Casas J., Carballeira J., Denia F.D., Thompson D.J. (2021), Railway rolling noise mitigation through optimal track design, [in:] *Proceedings of the YIC 2021 – VI ECCOMAS Young Investigators Conference*, https://doi.org/10.4995/YIC2021.2021.12583.

2. Basner M. *et al.* (2014), Auditory and non-auditory effects of noise on health, *The Lancet*, **383**(9925): 1325–1332, https://doi.org/10.1016/S0140-6736(13)61613-X.

3. Bunn F., Zannin P.H.T. (2016), Assessment of railway noise in an urban setting, *Applied Acoustics*, **104**: 16–23, https://doi.org/10.1016/j.apacoust.2015.10.025.

4. Cao L., Fu Q., Si Y., Ding B., Yu J. (2018), Porous materials for sound absorption, *Composites Communications*, **10**: 25–35, https://doi.org/10.1016/j.coco.2018.05.001.

5. Castiñeira-Ibáñez S., Rubio C., Romero-García V., Sánchez-Pérez J.V., García-Raffi L.M. (2012), Design, manufacture and characterization of an acoustic barrier made of multi-phenomena cylindrical scatterers arranged in a fractal-based geometry, *Archives of Acoustics*, **37**(4): 455–462, https://doi.org/10.2478/v10168-012-0057-9.

6. Fediuk R., Amran M., Vatin N., Vasilev Y., Lesovik V., Ozbakkaloglu T. (2021), Acoustic properties of innovative concretes: A review, *Materials*, **14**(2): 398, https://doi.org/10.3390/ma14020398.

7. Glickman G.M., Bensing S.J., Carman R. (2011), An examination of trackbed sound absorptive panels for minimizing wayside noise from rail transit, [in:] *NoiseCon Conference*.

8. Kraśkiewicz C. *et al.* (2024), Field experiment as a tool to verify the effectiveness of prototype track structure components aimed at reducing railway noise nuisance, *Archives of Acoustics*, **49**(1): 61–71, https://doi.org/10.24425/aoa.2024.148770.

9. Lee H.-J., Oh S.-T., Lee D.-J. (2016), An optimal mix design of sound absorbing block on concrete ballast in urban train tunnel, *Journal of Korean Tunnelling and Underground Space Association*, **18**(1): 75–82, https://doi.org/10.9711/ktaj.2016.18.1.075.

10. Leštinský L., Zvolenský P. (2019), New methods of noise reduction in railway carriages, *Transportation Research Procedia*, **40**: 778–783, https://doi.org/10.1016/j.trpro.2019.07.110.

11. Licitra G., Fredianelli L., Petri D., Vigotti M.A. (2016), Annoyance evaluation due to overall railway noise and vibration in Pisa urban areas, *Science of the Total Environment*, **568**: 1315–1325, https://doi.org/10.1016/j.scitotenv.2015.11.071.

12. Münzel T. *et al.* (2017), Effects of noise on vascular function, oxidative stress, and inflammation: Mechanistic insight from studies in mice, *European Heart Journal*, **38**(37): 2838–2849, https://doi.org/10.1093/eurheartj/ehx081.

13. Němec M., Danihelová A., Gergel' T., Gejdoš M., Ondrejka V., Danihelová Z. (2020), Measurement and prediction of railway noise case study from Slovakia, *International Journal of Environmental Research and Public Health*, **17**(10): 3616, https://doi.org/10.3390/ijerph17103616.

14. Shahidan S., Ramzi Hannan N.I.R., Md Maarof M.Z., Leman A.S., Senin M.S. (2017), A comprehensive review on the effectiveness of existing noise barriers commonly used in the railway industry, [in:] *MATEC Web of Conferences*, **87**: 01007, https://doi.org/10.1051/matecconf/20178701007.

15. Sun W., Liu L., Yuan H., Su Q. (2019), Influence of top shape on noise reduction effect of high-speed railway noise barrier, [in:] *IOP Conference Series: Materials Science and Engineering*, **493**(1): 012043, https://doi.org/10.1088/1757-899X/493/1/012043.

16. Sun Y., Yang L., Zheng J. (2020), Emission control areas: More or fewer?, *Transportation Research Part D: Transport and Environment*, **84**: 102349, https://doi.org/10.1016/j.trd.2020.102349.

17. Szczepański G., Podleśna M., Morzyński L., Włudarczyk A. (2023), Investigation of the acoustic properties of a metamaterial with a multi-ring structure, *Archives of Acoustics*, **48**(4): 497–507, https://doi.org/10.24425/aoa.2023.146814.

18. Vogiatzis K., Vanhonacker P. (2016), Noise reduction in urban LRT networks by combining track based solutions, *Science of the Total Environment*, **568**: 1344–1354, https://doi.org/10.1016/j.scitotenv.2015.05.060.

19. Zhang X., Thompson D., Quaranta E., Squicciarini G. (2019), An engineering model for the prediction of the sound radiation from a railway track, *Journal of Sound and Vibration*, **461**: 114921, https://doi.org/10.1016/j.jsv.2019.114921.

20. Zhao C., Wang P., Wang L., Liu D. (2014), Reducing railway noise with porous sound-absorbing concrete slabs, *Advances in Materials Science and Engineering*, **2014**: 206549, https://doi.org/10.1155/2014/206549.

21. Zvolenský P., Grenčík J., Pultznerová A., Kašiar L. (2017), Research of noise emission sources in railway transport and effective ways of their reduction, [in:] *MATEC Web of Conferences*, **107**: 00073, https://doi.org/10.1051/matecconf/201710700073.