Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal, 2026, 20(9), 134–148
https://doi.org/10.12913/22998624/222265
ISSN 2299-8624, License CC-BY 4.0

Received: 2026.02.20
Accepted: 2026.07.10
Published: 2026.08.01

Sound absorption properties of three-layer particleboard composites modified with recycled rubber and polymer waste from the automotive sector

Tomasz Szul[1*], Anna Darabošová[2], Iveta Čabalová[2], Miroslav Němec[3]

[1] Faculty of Production and Power Engineering, University of Agriculture, ul. Balicka 116b, 30-149 Kraków, Poland
[2] Department of Chemistry and Chemical Technologies, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia
[3] Department of Physics, Electrical Engineering and Applied Mechanics, Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24, 960 01 Zvolen, Slovakia
* Corresponding author's e-mail: t.szul@urk.edu.pl

ABSTRACT

The growing volume of end-of-life rubber and polymer waste from the automotive sector, combined with increasing demand for acoustic comfort in buildings, motivates the development of sustainable composite materials that integrate waste valorization with improved functional performance. The objective of this study was to systematically compare the effect of nine distinct types of recycled rubber and polymer waste granules — including tire rubber, rubber seals, painted and unpainted bumpers, fuel tanks, and cable insulation — introduced at 10% by volume into the core layer of three-layer particleboard, on the sound absorption properties of the resulting composites. Samples with a thickness of 18 mm were tested using the impedance tube method in accordance with ISO 10534-2 over the frequency range of 125–4000 Hz. Acoustic performance was evaluated using the frequency-dependent sound absorption coefficient α(f), the weighted absorption coefficient αw (ISO 11654), and the NRC index (ASTM C423). The results showed an increase in absorption with frequency, consistent with porous composite behavior. Among all variants, granules from waste rubber seals (SCG) achieved the highest performance, reaching an average value of $\alpha = 0.251$ in the range of 1000–2000 Hz and NRC = 0.35, which represents an improvement of approximately 80% compared to the unmodified reference board (NRC = 0.15). Tire-derived granules (T, TG) demonstrated stable broadband effectiveness (NRC = 0.30), while the addition of graphite did not yield statistically significant improvement. Rigid polymer granules (painted bumpers, cable insulation) showed no meaningful acoustic enhancement. One-way ANOVA with Tukey HSD post-hoc analysis confirmed statistically significant differences ($p < 0.001$, partial $\eta^2 = 0.78$) between rubber-based and polymer-based modifier groups in the 1000–2000 Hz range. The maximum αw value of 0.20 classifies the best-performing variants as class E (ISO 11654). Although absolute absorption remains moderate, the results demonstrate that selected elastomeric waste fractions can meaningfully enhance the sound-damping properties of structural particleboard, positioning these composites as functional elements in layered building systems within a circular economy framework.

Keywords: particleboard, sound absorption coefficient, wood-based composites, recycled rubber waste, automotive waste recycling, impedance tube method, circular economy.

INTRODUCTION

The increasing demand for acoustic comfort in residential and commercial buildings, driven by both regulatory requirements and occupant well-being considerations, has stimulated research into novel building materials with improved sound-absorbing properties. Simultaneously, the automotive end-of-life waste stream generates substantial volumes of rubber (tires, seals, gaskets) and mixed polymer components (bumpers, dashboards, cable insulation) that are resistant to biodegradation and pose significant disposal challenges [1, 2]. The convergence of these two drivers — the need for acoustic functionality and the imperative of waste valorization — creates a compelling rationale for investigating the incorporation of automotive rubber and polymer waste into construction materials.

Particleboard (chipboard) is one of the most widely used wood-based panel products in European construction. Its applications range from wall sheathing and flooring substrates to furniture and interior partitions. However, the sound absorption capacity of standard particleboard is inherently limited, especially in the mid and high frequency ranges, due to its relatively dense, closed structure that restricts viscous-thermal energy dissipation [3, 4]. Modification of the panel microstructure through the introduction of viscoelastic additives represents a promising strategy to enhance acoustic performance while maintaining the structural and manufacturing advantages of particleboard.

The potential of recycled rubber as a sound-absorbing material has been established in several material systems. Hassan and Rodrigue [1] point out that used car tires, although they are a problematic waste stream, have mechanical and viscoelastic properties that can be used in construction composites. Analyses by Wiśniewska et al. [2] and Sienkiewicz et al. [5] show that rubber recycling promotes the formation of materials with increased vibration damping capacity, which in the context of acoustics means effective conversion of acoustic wave energy into internal losses. Benazzouk et al. [6] experimentally confirmed that the addition of shredded rubber to cement composites reduces the modulus of elasticity and increases vibration damping capacity, which translates into improved acoustic parameters in the mid-frequency range. Sukontasukkul [7] confirmed that crumb rubber addition to concrete panels enhances both thermal insulation and sound absorption, with the effect proportional to rubber content up to approximately 20%.

Swift et al. [3] showed that the absorption efficiency of rubber granules depends on grain size, porosity, and air flow resistance, with the highest absorption coefficients obtained in the mid- and high-frequency ranges typical of open-cell granular materials. Similar observations were reported by Maderuelo-Sanz et al. [8], who analyzed composites made of rubber granules and polyurethane resin — a properly formed porous structure allows for significant absorption values to be achieved with panels of small thickness. Studies by Ružickij et al. [9] indicate that tire waste, including fiber and rubber fractions, can achieve NRC values of 0.3–0.5 with the appropriate structural configuration.

In wood-based composites specifically, Xu et al. [4] showed that perforated composites containing recycled rubber and HDPE achieve higher absorption coefficients than traditional wood-based panels, which is related to the porosity and presence of microcracks in the structure. Ghofrani et al. [10] showed that the addition of granules from used tires to plywood leads to an increase in sound absorption above 1000 Hz by scattering waves in a multiphase structure and increasing hysteresis losses. In the case of WPC (wood–plastic composites), studies by Daeipor et al. [11] and Danihelová et al. [12] indicate that the polymer phase content and porosity level have a key impact on acoustic parameters. A properly designed microstructure makes it possible to achieve properties comparable to those of industrial-grade sound-absorbing materials. Recent work by Badida et al. [13] on soundproofing materials using recycled automotive rubber confirmed that elastomeric waste maintains favorable acoustic energy dissipation characteristics even after mechanical recycling.

Polymer waste from the automotive sector (ABS, PP, PE) [13, 14] and construction (PVC/PE) [15, 16] exhibit favorable processing and mechanical properties, but acoustic performance depends on the porosity and structure of the composite core, as well as the volume fraction and particle distribution. However, the acoustic performance of such rigid polymer granules incorporated into wood-based panels has received limited attention, and their effectiveness relative to elastomeric (rubber) waste fractions has not been systematically established.

Despite the growing body of research on rubber-modified composites, several important gaps remain in the current state of knowledge. First, no study has systematically compared, within a uniform three-layer particleboard matrix produced under identical manufacturing conditions, the acoustic performance of multiple distinct types of rubber and polymer waste originating from the automotive end-of-life stream. Previous works have typically examined one or two waste types, often in cement, single-layer, or non-wood matrices. Second, comprehensive acoustic characterization using multiple standardized indices (frequency-dependent α(f), weighted αw according to ISO 11654, and NRC according to ASTM C423) supported by rigorous statistical analysis (ANOVA with post-hoc testing and effect size estimation) has rarely been reported for such composites. Third, the relative effectiveness of elastomeric versus rigid polymer waste fractions as acoustic modifiers in particleboard has not been established, which limits the ability to formulate evidence-based recommendations for waste stream selection in industrial practice.

The aim of this study is therefore to systematically compare the effect of nine different types of rubber and polymer waste granules from the automotive sector on the sound absorption properties of three-layer particleboard. The specific objectives are: (i) to determine the frequency-dependent sound absorption coefficient α(f) in the range of 125–4000 Hz for each waste type; (ii) to evaluate synthetic acoustic indices (αw, NRC) enabling standardized comparison; (iii) to identify the waste fractions with the highest acoustic potential and establish a performance ranking; and (iv) to assess the statistical significance of the observed differences using analysis of variance with post-hoc testing.

MATERIALS AND METHODS

Preparation of materials and research samples

The experiment used wood particles prepared from fresh spruce logs. The dimensions of the particles, commonly used to produce the core layer and selected for the production of single-layer chipboard, ranged from 0.25 mm to 4.0 mm. The wood particles were dried to a moisture content of 4% (±0.5%), which ensured the stability of the bonding process and the repeatability of the physical and mechanical parameters of the composites.

Granules with a size of 1–3 mm, made of a mixture of rubber waste (including car carpets and insulation elements), insulation from electrical cables (combustible and non-combustible), and shredded used car tires, were used as a modifying additive. The granules were pre-sieved to ensure homogeneity of the fraction and even distribution in the core layer structure.

A commercial urea-formaldehyde (UF) resin, Kronores CB 1100 F, was used to press single-layer PB boards with the addition of shredded plastic. The resin parameters were as follows: solid content – 67.1%, viscosity – 460 mPa·s, condensation time – 55 s, pH value – 8.6. The adhesive mixture contained ammonium nitrate NH_4NO_3 (47%) as a hardener and paraffin emulsion (30%) to improve moisture resistance.

Next, three-layer chipboards with the addition of shredded rubber and/or plastics, measuring 360 × 280 mm × 18 mm, were prepared. The nominal density of the boards was set at 650 kg/m³, which corresponds to typical values for structural particle boards used in construction. Although this study prioritizes acoustic performance, the maintenance of a density of 650 kg/m³ (±3%) and the use of a standard industrial pressing cycle (230 °C, 20 MPa) were intended to ensure the boards meet basic structural requirements. Preliminary evaluation suggests that a 10% volume substitution of wood particles does not prevent the composite from reaching the threshold for P2-type boards (EN 312), although full mechanical certification (Internal Bond and MOR) is the subject of ongoing research.

The actual density of each board was determined based on weight and volume measurements after seasoning; the deviation from the nominal value did not exceed ±3%. Maintaining a constant density was crucial for an unambiguous assessment of the effect of the granulate additive on the acoustic properties, eliminating the influence of structure compaction as a confounding factor. The wood-based composites were manufactured using standard industrial technology involving initial cold pressing of particle mats at a pressure of 1 MPa, followed by hot pressing in a CBJ 100–11 laboratory press.

The top layer was produced by mixing wood particles with an adhesive mixture in a laboratory coating drum. The middle layer was prepared from wood particles, crushed rubber polymer granules, and an adhesive mixture, which were thoroughly homogenized in the same type of device. Waste additives were introduced only into the middle layer of the board in an amount of 10% by volume relative to the volume of this layer, which allowed for an unambiguous assessment of the effect of the type of additive.

A single modifier content of 10% by volume relative to the core layer was adopted in this study. This level was selected based on preliminary trials indicating that it represents a balance between introducing a sufficient quantity of elastomeric phase to influence acoustic behavior and maintaining adequate board cohesion during pressing. Higher volume fractions (≥15%) led to visible delamination in preliminary tests, likely due to poor interfacial adhesion between the UF resin matrix and hydrophobic rubber/polymer surfaces. The 10% level also corresponds to the range used in comparable studies on rubber-modified wood composites (Ghofrani et al. [10]: 5–15%; Xu et al. [4]: 10–20%). The single-level design was deliberately chosen to isolate the effect of waste type as the primary independent variable, while optimization of the volume fraction constitutes a planned follow-up study. Based on general trends reported in the literature, increasing rubber content typically enhances sound absorption up to an optimum point (approximately 15–25% depending on particle size and matrix type), beyond which mechanical integrity deterioration outweighs acoustic gains [3, 7].

Nine types of waste additives were used. Table 1 presents their characteristics, including source, polymer/elastomer classification, granule size, and macroscopic appearance.

All waste materials were previously crushed into granules with a comparable grain size range (fine fraction) to limit the impact of geometric differences between particles on the acoustic measurement results. The granules were evenly mixed with the chip material intended for the middle layer of the board and then subjected to hot pressing at constant technological parameters (temperature, pressure, and pressing time identical for all variants). The distribution of granules in the board cross-section (Figure 1) was assessed visually after cutting the samples, and no macroscopic particle clusters were found.

Six independent samples were prepared for each type of composite, cut from different sections of the same board, which made it possible to assess the repeatability of the results and the impact of the heterogeneity of the granule distribution. A similar number of samples were prepared for the reference board (P). A surface layer weighing 396 g was applied to the bottom of the mold, followed by a middle layer weighing 1110 g, and finally another surface layer weighing 396 g, ensuring a symmetrical plate structure.

The formed mat was pre-pressed in a hydraulic pre-press for approximately 2 minutes. After the forming stage, hot pressing was carried out at variable pressure levels: 20 MPa, 10 MPa, and 5 MPa in successive phases of the pressing cycle. The total pressing time was 5 minutes at a temperature of 230 °C. These parameters were selected to ensure adequate compaction of the composite structure and proper polycondensation of the UF resin.

After the pressing process was completed, the boards were seasoned under laboratory conditions (20 ± 2 °C, relative humidity 65 ± 5%) until hygroscopic equilibrium was reached and then samples for acoustic testing were cut out (Figure 2).

Samples for the impedance tube were cut with a dimensional tolerance of ±0.1 mm relative to the inner diameter of the tube, and their thickness was checked at four points using a micrometer; the thickness deviation did not exceed ±0.2 mm, which ensured a tight fit of the sample to the tube walls and minimized the impact of leaks on the sound absorption coefficient measurement result.

Measurement setup and test procedure

Sound absorption coefficient measurements were performed using the impedance tube method in accordance with ISO 10534-2:2023 [17]. This

Table 1. Characteristics of waste granule types used as core-layer modifiers

Designation	Waste source	Polymer/elastomer type	Granule size (mm)	Macroscopic appearance
PB	Painted car bumpers	PP/PE blend with paint layer	1–3	Angular, smooth surfaces
UB	Unpainted car bumpers	PP	1–3	Angular, smooth surfaces
FT	Fuel tanks	HDPE	1–3	Irregular, semi-rigid
CEN	Non-flammable power cables	PVC/mineral-filled PE	1–3	Irregular, multi-material
CIF	Flammable power cables	PE/PVC	1–3	Irregular, multi-material
T	Used car tires	Vulcanized SBR/NR rubber	1–3	Irregular, fibrous fracture surface
SC	Car seals and linings	EPDM/NR rubber blend	1–3	Irregular, porous
TG	Tires with graphite additive	SBR/NR rubber + graphite	1–3	Irregular, fibrous fracture surface
SCG	Waste rubber seals	EPDM rubber	1–3	Irregular, highly porous

Figure 1. Macroscopic view of the cross-section of selected samples

method was used due to the laboratory nature of the tests, the limited dimensions of the samples, and the purpose of the work, which was to comparatively assess the impact of the type of waste admixture on the acoustic properties of the material, rather than to determine the performance parameters in diffuse field conditions.

The tests were performed using a Brüel and Kjær impedance tube equipped with two measuring microphones. Two geometric configurations of the tube were used:

- samples with a diameter of 100 mm for the frequency range 20–1600 Hz,
- samples with a diameter of 30 mm for the frequency range 1600–6400 Hz.

This solution made it possible to obtain continuous sound absorption characteristics over a wide frequency range, which is important from the point of view of building acoustics. The thickness of all samples was 18 mm and corresponded to the thickness of the tested panels.

The impedance tube method allows for precise determination of the sound absorption coefficient for perpendicular incidence of the acoustic wave. The authors are aware that these results may differ from the values obtained in a reverberation chamber (ISO 354 [18]), but the method used is widely accepted in comparative and material tests and allows for the analysis of the influence of the microstructure of the material on sound absorption.

For each material variant, six independent samples were tested. Each sample was measured three times, and the average of the three measurements was taken as the representative value for that sample. The microphone calibration was verified at the beginning of each measurement session using the standard switch-channel technique prescribed by ISO 10534-2 [17].

Acoustic property assessment methods

The acoustic properties of the materials were assessed based on:

- the frequency characteristics of the sound absorption coefficient α(f), determined as a function of frequency based on measurements made using the impedance tube method,

Figure 2. View of sample specimens for acoustic testing

- weighted sound absorption coefficient αw and the corresponding sound absorption class (A–E), determined in accordance with PN-EN ISO 11654 [19]. It should be noted that both αw (ISO 11654) and NRC (ASTM C423) are conventionally derived from random-incidence sound absorption coefficients measured in a reverberation chamber (ISO 354 [18]). In the present study, these indices were calculated from normal-incidence data obtained via the impedance tube method (ISO 10534-2 [17]). This approach is widely adopted in comparative material screening studies where reverberation chamber testing is impractical due to limited sample dimensions (e.g., Xu et al. [4]; Ghofrani et al. [10]; Badida et al. [13]). The resulting αw and NRC values serve as relative ranking indices enabling inter-material comparison within this study; however, they should not be directly equated with values obtained under diffuse-field conditions. This caveat is explicitly stated wherever αw or NRC values are discussed. Strictly speaking, the reported αw and NRC should be treated as 'impedance tube-derived indices'. Users are cautioned against using these values for room acoustic design simulations, as they represent the material's response only to normal-incidence waves and do not account for the sound field diffusion effects present in standard ISO 354 tests.
- Noise Reduction Coefficient (NRC), determined in accordance with ASTM C423 [20] as the arithmetic mean of sound absorption coefficients in octave bands of 250, 500, 1000, and 2000 Hz, which is a supplementary index enabling comparison of the obtained results with literature data and tests conducted according to American standards.

The use of three complementary assessment indicators allowed for a multifaceted analysis of the sound absorption properties of the tested composites and ensured that the interpretation of the results was consistent with current European and American standards.

RESULTS

Frequency characteristics of sound absorption coefficient α(f)

The analysis covered the sound absorption coefficient α(f) in the range of 125–4000 Hz (octave bands), determined using the impedance tube method. Figure 3 shows the mean absorption values for ten material variants in the form of a grouped bar chart, with error bars representing ±1 standard deviation (SD). Materials are color-coded: rubber-based granules (T, TG, SC, SCG) are shown in warm colors, rigid polymer granules (PB, UB, FT, CEN, CIF) in cool colors, and the reference sample (P) in gray.

In all tested materials, a general trend of increasing sound absorption coefficient with

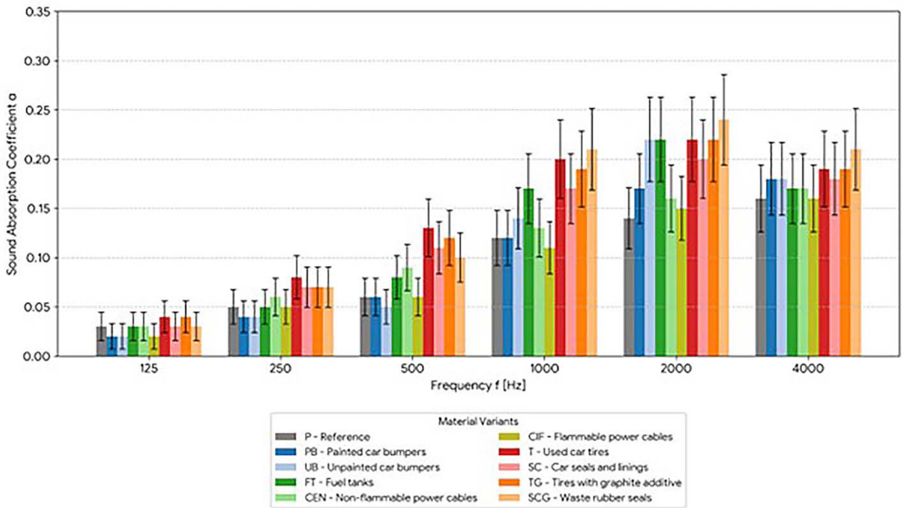

Figure 3. Comparison of mean sound absorption coefficients α(f) for the tested samples in octave bands (125–4000 Hz). Error bars represent ±1 standard deviation (n = 6 per variant). Rubber-based modifiers are shown in warm colors (red/orange tones), polymer-based modifiers in cool colors (blue/green tones), reference sample (P) in gray

increasing frequency is observed. This phenomenon is typical for materials with a porous or composite structure and results from viscoelastic loss mechanisms and friction losses at higher frequencies. While the enhancement in SCG and T variants is attributed to internal friction and viscoelastic damping within the elastomeric phase, these mechanisms are currently inferred from the macroscopic acoustic response. In the absence of micro-imaging data (e.g., SEM), the specific role of interfacial bonding and microscopic pore geometry remains a probable explanation that requires further confirmation.

In the low frequency range (125–500 Hz), the α(f) values remain relatively low ($\alpha \leq 0.13$), which should be associated with the limited thickness of the boards (18 mm) and the lack of an additional air layer. In this band, the differences between the materials are relatively small, although the highest values were consistently achieved by granules from used car tires (T), followed by TG and SC. The reference sample (P) had some of the lowest values in this range. In the mid and high frequency range (1000–4000 Hz), the differences between the materials become more pronounced. The highest α(f) values were obtained for granules from waste rubber seals (SCG), which reached: 0.21 at 1000 Hz, 0.24 at 2000 Hz, and 0.21 at 4000 Hz. The values reported above refer to octave band center frequencies and have been rounded to two decimal places. The mean value of $\alpha = 0.251$ reported in Table 2 for the 1000–2000 Hz range was calculated from measurements in one-third octave bands (1000, 1250, 1600, and 2000 Hz), which includes additional measurement points within this range and explains the higher mean value compared to the simple average of two octave bands $(0.21 + 0.24) / 2 = 0.225$.

In the same bands, the reference sample (P) achieved 0.12, 0.14, and 0.16, respectively, confirming the improvement in absorption properties for selected rubber additives.

The T and TG granules showed consistently higher values across the entire analyzed range, indicating their broadband nature. The addition of graphite (TG) did not cause a significant change in the characteristics compared to pure tire granules (T). Materials such as PB, UB, and CIF showed characteristics similar to the reference sample, suggesting that their structure (more compact, less flexible) is not conducive to the intensification of acoustic energy absorption mechanisms.

The variability of the results, represented by the standard deviation, was greater in the low frequency range, while in the range of 1000–4000 Hz, greater repeatability of measurements was observed.

Statistical analysis in the range of 1000–2000 Hz

The range of 1000–2000 Hz was considered crucial due to its significant contribution to the speech spectrum and typical sources of environmental and industrial noise.

Table 2 presents the average values of the sound absorption coefficient α(f), standard deviation (SD), and coefficient of variation (CV).

The highest average value in the analyzed range was obtained by SCG – 0.251, followed by: TG – 0.229; T – 0.228; FT – 0.227. For comparison, the reference sample (P) achieved a value of

Table 2. Average values of the sound absorption coefficient α in the frequency range of 1000–2000 Hz for the analyzed materials. Values were calculated as the mean of measurements in one-third octave bands at 1000, 1250, 1600, and 2000 Hz

Material	Average α(f)	Standard deviation (SD)	Coefficient of variation (CV) [%]
P	0.138	0.007	5.23
PB	0.153	0.016	10.25
UB	0.218	0.040	18.45
FT	0.227	0.035	15.23
CEN	0.145	0.015	10.18
CIF	0.127	0.012	9.21
T	0.228	0.021	9.26
SC	0.205	0.027	12.97
TG	0.229	0.031	13.73
SCG	0.251	0.030	12.00

0.138. This means an increase in absorption of 60–80% compared to the base material in the case of the best rubber variants. CIF granulate achieved a value of 0.127, lower than the reference sample, which indicates no positive effect of modification in this case.

Stability and dispersion of results

The coefficient of variation (CV) for most materials ranged from 9% to 15%, which can be considered moderate variability in properties. The lowest variability was observed in the reference sample (5.23%), which is typical for structurally homogeneous material.

The highest variability was observed for UB (18.45%), which may indicate greater microstructural heterogeneity or a more complex mechanism of acoustic wave interaction with the material. It is important to note that the lack of direct microstructural characterization is a limitation of this study. Future research involving cross-sectional microscopy would be essential to validate the proposed physical models of sound dissipation in these specific multiphase systems.

Full statistical analysis

One-way analysis of variance (ANOVA) was performed to evaluate the effect of modifier type on the mean sound absorption coefficient in the 1000–2000 Hz range. The full ANOVA results are presented in Table 3.

The large effect size (partial $\eta^2 = 0.78$) indicates that the type of waste modifier accounts for approximately 78% of the total variance in sound absorption coefficient in this frequency range, which according to Cohen's conventions represents a large effect. Post-hoc analysis using the Tukey HSD test (Table 4) identified two statistically distinct homogeneous subsets of materials.

Means within the same subset (column) do not differ significantly from each other (Tukey HSD, $p > 0.05$). Group A comprises all rubber-based granules (SCG, T, TG, SC) and two polymer types with intermediate flexibility (FT, UB). Group B comprises the reference sample and rigid polymer granules (PB, CEN, CIF).

ANOVA per individual octave bands

To examine how the effect of modifier type varies across the frequency spectrum, one-way ANOVA was also performed independently for each octave band. The results are presented in Table 5. The per-band ANOVA results reveal a non-monotonic, frequency-dependent pattern of the modifier effect, with several noteworthy features:

At 125 Hz, the ANOVA result was not statistically significant ($F(9,50) = 1.61$, $p = 0.137$), confirming that at very low frequencies – where the acoustic wavelength (~2.75 m) greatly exceeds the sample thickness (18 mm) – the type of core-layer modifier has no detectable influence on absorption. This is consistent with the theoretical expectation that low-frequency absorption in thin panels is governed primarily by the overall panel stiffness and mass, rather than by the microstructure of the core layer.

At 250 Hz, the highest F-statistic across all bands was observed ($F = 23.97$, $\eta^2 = 0.81$), with four materials (SCG, T, TG, UB) differing significantly from the reference. It should be noted that measurements at both 125 Hz and 250 Hz were performed using the same impedance tube

Table 4. Tukey HSD post-hoc grouping of materials based on mean α in the 1000–2000 Hz range (critical difference $HSD_{0.05} = 0.049$)

Material	Mean α	Group A	Group B
SCG	0.251	×	
TG	0.229	×	
T	0.228	×	
FT	0.227	×	
UB	0.218	×	
SC	0.205	×	
PB	0.153		×
CEN	0.145		×
P	0.138		×
CIF	0.127		×

Table 3. One-way ANOVA results for mean sound absorption coefficient in the 1000–2000 Hz range

Source	SS	df	MS	F	p	Partial η²
Between groups	0.1145	9	0.01272	19.48	< 0.001	0.78
Within groups	0.0327	50	0.000653			
Total	0.1472	59				

Table 5. One-way ANOVA results across individual octave bands

Frequency (Hz)	F(9,50)	p	Partial η²	Significant post-hoc pairs vs. P (Tukey HSD)
125	1.61	0.137	0.23	none
250	23.97	< 0.001	0.81	SCG, T, TG, UB
500	7.90	< 0.001	0.59	T, TG
1000	6.40	< 0.001	0.54	SCG, T, TG
2000	13.35	< 0.001	0.71	FT, SC, SCG, T, TG, UB
4000	3.06	< 0.005	0.36	SCG

configuration (100 mm diameter, working range 20–1600 Hz), which rules out artifacts arising from a change in measurement geometry as a potential source of the observed F-statistic peak at 250 Hz. This unexpectedly strong effect at a relatively low frequency may indicate a resonance-type absorption mechanism associated with the mass-spring interaction between dense elastomeric inclusions and the surrounding chip-resin matrix. At this frequency, the viscoelastic rubber particles embedded in the stiffer wood-chip matrix may undergo localized resonant oscillation, enhancing energy dissipation through hysteresis losses. The presence of UB (a relatively rigid PP granulate) among the significant pairs at 250 Hz – but not at 500 or 1000 Hz – suggests that different modifier types may engage different absorption mechanisms at different frequencies. However, this interpretation remains hypothetical in the absence of dynamic mechanical analysis (DMA) or microstructural imaging.

At 500 and 1000 Hz, the F-statistic decreases (7.90 and 6.40, respectively), with fewer significant post-hoc pairs (only T, TG at 500 Hz; SCG, T, TG at 1000 Hz). This intermediate region may represent a transition zone between the resonance-dominated regime (250 Hz) and the viscous-thermal dissipation regime (2000 Hz), where the absorptive advantage of the modified composites is temporarily attenuated.

At 2000 Hz, the F-statistic recovers to 13.35 ($\eta^2 = 0.71$), and the largest number of materials (six: FT, SC, SCG, T, TG, UB) differ significantly from the reference sample. This frequency band corresponds to the classical regime of viscous-thermal energy dissipation in porous composites, where the inter-particle tortuosity, airflow resistivity, and surface morphology of the modifier granules play a dominant role. The broad significance at this frequency is consistent with the literature on rubber-modified composites [3, 10, 13].

At 4000 Hz, the F-statistic drops to 3.06 ($p < 0.005$, $\eta^2 = 0.36$), with only SCG remaining significantly different from the reference. At high frequencies, all tested composites — including the unmodified reference — tend toward higher absorption due to the inherent properties of the wood-chip surface layers (identical across all variants), which reduces the inter-variant differences.

The non-monotonic pattern (125 → 250 ↑↑ → 500 ↓ → 1000 ↓ → 2000 ↑ → 4000 ↓) suggests that at least two distinct absorption mechanisms contribute to the acoustic performance of the modified composites: a resonance-type mechanism prominent at lower frequencies (~250 Hz) and a classical viscous-thermal mechanism dominant at higher frequencies (~2000 Hz). Similar bimodal patterns have been reported for elastomer-modified cement composites [6, 7].

It should be noted that the F-statistic for the aggregate 1000–2000 Hz range (Table 3: F = 19.48) is higher than the F values for the individual 1000 Hz and 2000 Hz bands (6.40 and 13.35, respectively). This is not inconsistent: the averaging of α values across the 1000–2000 Hz range reduces within-group (error) variance – because random measurement fluctuations at individual frequencies partially cancel out – while preserving the systematic between-group differences, thereby increasing the signal-to-noise ratio and yielding a higher F-statistic.

Weighted sound absorption coefficient αw and absorption classes

Table 6 shows the αw values and absorption classes in accordance with PN-EN ISO 11654 [19]. As noted in Section 2.3, αw was determined from normal-incidence data and serves as a comparative index; the classification does not replace assessment by the reverberation chamber method (ISO 354 [18]). None of the tested materials achieved high absorption classes (A–D). Most of the modified composites were classified as class E (αw = 0.15–0.20), while the reference sample and the PB, UB, and CIF materials remained unclassified (αw = 0.10).

The highest αw value (0.20) was obtained for the T, TG, and SCG materials. However, it should be emphasized that the classification according to PN-EN ISO 11654 is comparative in nature, refers to the characteristics of perpendicular acoustic wave incidence, and is not identical to the classification obtained using the reverberation chamber method (ISO 354 [18]). The results indicate that the addition of selected rubber granules improves the sound-absorbing properties of chipboard, but the level of improvement remains moderate in terms of standards.

Table 6. Weighted sound absorption coefficient αw and corresponding absorption classes of the tested materials

Material	Coefficient αw	Sound absorption class (A–E)
P	0.10	Unclassified
PB	0.10	Unclassified
UB	0.10	Unclassified
FT	0.15	E
CEN	0.15	E
CIF	0.10	Unclassified
T	0.20	E
SC	0.15	E
TG	0.20	E
SCG	0.20	E

Noise reduction coefficient (NRC)

To synthetically evaluate the acoustic performance of the tested materials, the noise reduction coefficient (NRC) was determined, calculated as the arithmetic mean of the sound absorption coefficients in the octave bands of 250, 500, 1000, and 2000 Hz. This parameter, widely used in acoustic engineering practice, allows for the comparison of materials regarding their overall effectiveness in frequency ranges significant for traffic noise, industrial noise, and the speech band. Table 7 presents the NRC values along with the SD.

Table 7. Noise reduction coefficient (NRC) values for individual materials

Material	Mean NRC	Standard deviation SD
P	0.15	0.02
PB	0.15	0.02
UB	0.20	0.03
FT	0.20	0.03
CEN	0.15	0.02
CIF	0.15	0.02
T	0.30	0.04
SC	0.25	0.03
TG	0.30	0.04
SCG	0.35	0.05

The summary of results in Table 7 indicates a clear differentiation in the effectiveness of the tested granulates. The highest NRC value was achieved by the granulate from waste rubber seals (SCG), with NRC = 0.35 (SD = 0.05). The next group consists of tire-derived granulates: T and TG, with NRC = 0.30 (SD = 0.04). The granulate from waste seals and floor coverings (SC) reached NRC = 0.25 (SD = 0.03), while materials UB and FT obtained NRC = 0.20 (SD = 0.03). The lowest values (NRC = 0.15; SD = 0.02) were recorded for the reference sample P and materials PB, CEN, and CIF. These results are consistent with the band analysis presented in sections 3.1–3.3. Materials SCG, T, and TG, which exhibited the highest absorption coefficients in the 1000–2000 Hz range, also achieved the highest NRC values. This confirms their broadband effectiveness in the mid-frequency range, which is decisive for the global assessment of sound absorption.

Figure 4 presents a radar (spider) chart comparing the NRC values across all ten material

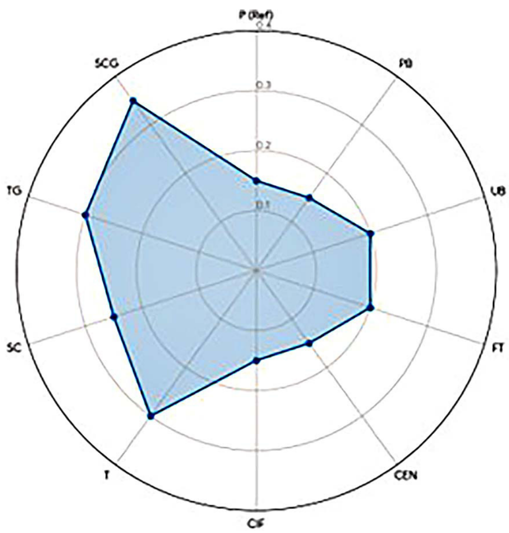

Figure 4. Radar chart comparing noise reduction coefficient (NRC) values for all tested material variants. The radial axis represents NRC (0–0.40). The chart visually highlights the superior performance of rubber-based modifiers (SCG, T, TG, SC) relative to the reference sample (P) and rigid polymer modifiers (PB, CEN, CIF)

variants, enabling rapid visual identification of the best-performing waste types.

DISCUSSION

Frequency-dependent absorption behavior and physical interpretation

The obtained frequency characteristics of the sound absorption coefficient α(f) show a pattern typical for porous and composite materials – low efficiency in the range of 125–500 Hz and a marked increase in efficiency in the 1000–4000 Hz band. This distribution is consistent with classical absorption models describing the dominance of viscous-thermal losses and intergranular friction at higher frequencies, as analyzed in detail by Swift et al. [3] and Xu et al. [4].

In the analyzed composites, the introduction of elastomeric granules into the particleboard core layer is hypothesized to modify the internal microstructure in several ways that may enhance sound absorption: (i) the creation of additional interstitial voids and tortuous air pathways at the granule–wood particle interface, increasing airflow resistivity and promoting viscous dissipation; (ii) the introduction of a viscoelastic phase capable of converting mechanical vibration energy into heat through hysteresis losses in the elastomer; and (iii) the disruption of the relatively homogeneous chip matrix, promoting wave scattering at phase boundaries. However, it should be clearly emphasized that no direct microstructural studies (e.g., SEM) or air flow resistance (R_f) measurements were performed in this work, therefore the above interpretation of energy dissipation mechanisms is indirect and based on literature analysis and macroscopic observations of sample cross-sections. This constitutes a recognized limitation discussed further.

It should be emphasized that the proposed interpretation of absorption mechanisms — although indirect in the present study – is grounded in well-documented structure–property relationships that have been experimentally confirmed in analogous material systems. Swift et al. [3] performed airflow resistivity measurements on recycled rubber granulate layers and demonstrated that airflow resistivity is the primary parameter governing sound absorption in the mid- and high-frequency ranges. Benazzouk et al. [6] confirmed through SEM imaging that the addition of shredded rubber to a cement matrix creates additional pores and interfacial gaps responsible for enhanced absorption. Sukontasukkul [7] measured the porosity of concrete panels with crumb rubber and demonstrated its correlation with sound absorption. The extrapolation of these mechanisms to a particleboard system modified with analogous elastomeric granules is physically justified, although it requires direct validation in future studies.

The per-band ANOVA results (Table 5) provide additional insight into the physical mechanisms underlying the observed acoustic improvement. The non-monotonic frequency profile of the F-statistic – with peaks at 250 Hz and 2000 Hz separated by a relative minimum at 500–1000 Hz – suggests that at least two complementary mechanisms contribute to sound absorption in these composites. The first mechanism, prominent at 250 Hz, may be attributed to a resonant interaction between the dense elastomeric inclusions and the surrounding chip-resin matrix, where the rubber particles function as localized mass-spring oscillators dissipating energy through hysteresis. The second mechanism, dominant at 2000 Hz, corresponds to the classical viscous-thermal dissipation regime in which sound energy is converted to heat through air oscillation in tortuous inter-particle channels. The transition zone at 500–1000 Hz, where neither mechanism fully dominates, results in a temporary reduction in the discriminatory power of the modifier type. This dual-mechanism interpretation is consistent with observations reported by Benazzouk et al. [6] for rubber-modified cement composites, where a similar bimodal frequency response was attributed to the interplay between elastic resonance and porous dissipation.

Comparative performance of waste types

The Tukey HSD post-hoc analysis (Table 4) for the aggregate 1000–2000 Hz range revealed two statistically distinct groups of materials. Group A, comprising all rubber-based granules (SCG, T, TG, SC) and two polymer types with intermediate flexibility (FT, UB), achieved significantly higher mean absorption coefficients (0.205–0.251) compared to Group B (P, PB, CEN, CIF; mean α = 0.127–0.153). The large effect size (partial $\eta^2 = 0.78$) confirms that waste type is the dominant factor determining acoustic performance in this frequency range.

The per-band analysis (Table 5) further refines this picture. While the aggregate analysis groups FT and UB together with rubber-based modifiers, the per-band results show that FT and UB reach statistical significance versus P only at 2000 Hz (and UB also at 250 Hz), whereas rubber-based modifiers T and TG are significant across a broader frequency range (250–2000 Hz). SCG is the only material significantly different from P at both frequency extremes where the ANOVA is significant (250 Hz and 4000 Hz), confirming its broadband superiority.

The highest values of α(f), as well as the synthetic indices αw and NRC, were obtained for SCG, T, and TG materials. Granules from rubber seal waste (SCG) showed the highest average efficiency in the range of 1000–4000 Hz, which may be related to the more developed structure of the particles and their elastic

Comparison with published data

Table 8 compares the acoustic performance of the present composites with values reported in the literature for analogous material systems containing recycled rubber.

The NRC value of 0.35 obtained for the SCG variant is comparable to the lower range of values reported by Ghofrani et al. [10] for plywood–tire rubber composites and by Ružickij et al. [9] for recycled tire textile fibers. However, it is substantially lower than values achieved by dedicated rubber granulate absorbers without a rigid matrix (Swift et al. [3]: NRC = 0.40–0.70; Maderuelo-Sanz et al. [8]: NRC = 0.45–0.75), which is expected given that the present composites are primarily structural panel materials with only 10% rubber content by volume in the core layer. The comparison confirms that particleboard modified with rubber waste occupies an intermediate functional niche – between conventional wood-based panels and dedicated acoustic absorbers – which is consistent with its intended application as a structural element with enhanced damping properties rather than a standalone absorber.

Notably, Badida et al. [13] reported sound absorption coefficients of 0.25–0.45 at 1000–2000 Hz for dedicated panels made entirely from recycled automotive rubber, which is 1.5–2 times higher than the values obtained in the present study. This confirms that the limiting factor in the present system is the low volumetric fraction of rubber (10%) and the constraining effect of the dense chip matrix, which restricts the formation of an interconnected porous network.

Practical significance and critical assessment

The weighted sound absorption coefficient αw (max. 0.20) values classify the tested materials as class E in accordance with PN-EN ISO 11654 [19]. It is important to contextualize these values within the broader landscape of acoustic materials. Commercial sound-absorbing panels (mineral wool, melamine foam, perforated panels with absorptive backing) typically achieve αw values of 0.70–1.00 (classes A–B). The composites investigated in this study do not approach such performance and should not be positioned as standalone acoustic absorbers.

Table 8. Comparison of acoustic performance with published data for rubber-modified composite panels

Reference	Material system	Thickness (mm)	NRC	Note
Present study (SCG)	Particleboard + EPDM seal rubber (10% vol.)	18	0.35	Three-layer board; impedance tube
Present study (T, TG)	Particleboard + tire rubber (10% vol.)	18	0.30	Three-layer board; impedance tube
Ghofrani et al. [10]	Plywood + tire rubber (5–15%)	16	~0.25–0.40	NRC estimated from α(f) data
Xu et al. [4]	Perforated composite + recycled rubber + HDPE	20	~0.35–0.55	Perforated panel design
Ružickij et al. [9]	Recycled tire textile fibers	30	0.30–0.50	Fiber-based, no rigid matrix
Swift et al. [3]	Recycled rubber granulate layers	25–50	0.40–0.70	Granulate only, no wood matrix
Maderuelo-Sanz et al. [8]	Rubber granulate + PU resin	20–40	~0.45–0.75	Dedicated absorber panel
Badida et al. [13]	Recycled automotive rubber panel	20–30	~0.30–0.55	Dedicated rubber-based panel
Sukontasukkul [7]	Concrete panel + crumb rubber	50	~0.25–0.40	Cement-based matrix

However, their practical value lies in a different functional niche. As structural or semi-structural panel materials, these modified particleboards can serve as elements in layered building assemblies where even modest improvements in surface absorption contribute to reduced reverberation and flutter echo. For example, in lightweight timber-frame partitions – where the inner lining may consist of particleboard rather than gypsum board – an 80% increase in mid-frequency absorption (as achieved by the SCG variant) can contribute to improved overall acoustic quality of the room. Potential applications include cladding in lightweight stud partitions, interior design elements, floor underlays, technical enclosures, and furniture components where it is essential to limit sound reflections in the mid-frequency range. In layered systems, particularly in combination with an air cavity or a thick, porous material, these composites can serve as a functional element improving the global acoustic characteristics of the partition while simultaneously utilizing recycled materials. The limited thickness of the samples (18 mm) and the lack of an air gap further determine the moderate level of synthetic indicators. The literature shows that increasing the thickness or using a layered system can lead to a significant increase in NRC values [9].

Recent advances in computational design of multilayer acoustic structures demonstrate that the frequency-dependent absorption characteristics of layered panels can be systematically optimized using heuristic methods. Grochowina and Leniowska [21] showed that genetic algorithms can identify near-optimal configurations of multilayer sound-absorbing structures with predefined frequency characteristics within a limited number of generations. This suggests that the composites developed in the present study, with their experimentally determined $\alpha(f)$ profiles, could serve as candidate component layers in computationally optimized multilayer building partitions, where their specific mid-frequency absorption enhancement would be matched with complementary porous or resonant layers to maximize the overall acoustic performance of the assembly.

From a circular economy perspective, the utilization of automotive end-of-life waste in particleboard production addresses two challenges simultaneously: reducing the volume of landfilled elastomeric waste and adding functional value to a commodity building product. The approach is aligned with the principles of the EU Circular Economy Action Plan and the End-of-Life Vehicles Directive (2000/53/EC), which mandate increasing recycling and recovery rates for automotive waste.

Limitations of the study

The present study was designed as a systematic screening study aimed at comparatively ranking nine types of waste according to their acoustic potential within a uniform particleboard matrix. The study was carried out during a research internship using the laboratory infrastructure available for acoustic measurements. Microstructural and mechanistic characterization exceeds the scope of the research objective as defined but constitutes a logical and planned next stage of research. The following specific limitations should be acknowledged:

- No microstructural characterization was performed. SEM imaging of sample cross-sections and fracture surfaces would provide direct evidence for the hypothesized mechanisms (inter-particle porosity, interfacial morphology, granule distribution). This is planned as a priority in follow-up work.
- Airflow resistivity (ISO 9053) and open porosity were not measured. These parameters are critical for quantitative modeling of sound absorption in porous media and would enable validation of the proposed mechanistic interpretation, including the bimodal frequency response observed in the per-band ANOVA (Table 5).
- Only one modifier content (10% vol.) was investigated. Although justified by the study design (isolation of waste-type effect at constant density), this prevents conclusions regarding the dose–response relationship between rubber content and acoustic performance.
- Mechanical properties (MOR, MOE, internal bond strength per EN 310 and EN 319) were not evaluated. While the maintained nominal density (650 kg/m³ ±3%) and absence of visible delamination suggest that the boards retain functional integrity, formal structural characterization is required before any load-bearing applications can be recommended. Literature evidence (Ayrilmis et al. [22]) indicates that rubber addition to wood-based panels at the 10% level causes a measurable decrease (approximately 20–30%) in MOR and MOE, which may be acceptable for non-structural applications but requires verification for the specific composites investigated here.

- The αw and NRC indices were derived from normal-incidence impedance tube measurements (ISO 10534-2 [17]) rather than random-incidence reverberation chamber data (ISO 354 [18]). The reported values serve as relative ranking indices for inter-material comparison and should not be directly equated with diffuse-field performance ratings.
- The study did not include quantitative particle size distribution analysis, dynamic mechanical analysis (DMA), or BET surface area measurements of the waste granules, which would enable more rigorous correlation of particle morphology and viscoelastic properties with acoustic performance and validation of the hypothesized dual-mechanism absorption model.

CONCLUSIONS

Based on a systematic comparison of nine types of recycled rubber and polymer waste granules from the automotive sector as core-layer modifiers in three-layer particleboard, the following conclusions are drawn:

1. The type of waste modifier has a statistically significant and practically meaningful effect on the sound absorption coefficient of particleboard. In the aggregate 1000–2000 Hz range, the modifier type accounts for 78% of the total variance (one-way ANOVA: $F(9,50) = 19.48$, $p < 0.001$, partial $\eta^2 = 0.78$). Per-band analysis confirmed significant effects at all octave bands from 250 to 4000 Hz, with the exception of 125 Hz ($p = 0.137$), where the limited sample thickness precludes meaningful differentiation.
2. Elastomeric (rubber-based) granules consistently outperform rigid polymer granules. The highest acoustic performance was achieved by granules from EPDM rubber seal waste (SCG), reaching an average value of α = 0.251 in the range of 1000–2000 Hz and NRC = 0.35 (SD = 0.05), representing an 80% improvement over unmodified particleboard (NRC = 0.15). Tire-derived granules (T, TG) achieved NRC = 0.30, while rigid polymer granules (PB, CIF) showed no significant improvement at any frequency band.
3. The addition of graphite filler to tire rubber granules (TG vs. T) did not produce a statistically significant effect on any acoustic parameter, confirming that viscoelastic properties of the elastomeric phase, rather than mineral additives, are the primary determinant of acoustic performance.
4. The maximum weighted sound absorption coefficient αw = 0.20 (absorption class E, ISO 11654) represents moderate absolute absorption. The tested composites are not standalone acoustic absorbers but may serve as structural panel elements with enhanced sound-damping properties in layered building systems and as candidate layers in computationally optimized multilayer partitions.
5. The per-band ANOVA revealed a non-monotonic frequency profile of the modifier effect, with peaks at 250 Hz and 2000 Hz, suggesting the coexistence of a resonance-type mechanism at lower frequencies and classical viscous-thermal dissipation at higher frequencies. The interpretation of these mechanisms remains indirect, as SEM imaging, airflow resistivity, DMA, and porosity measurements were not performed. However, the proposed mechanisms are consistent with relationships experimentally confirmed in analogous material systems. Microstructural characterization, mechanical property evaluation (MOR, MOE, IB), and optimization of modifier volume fraction constitute priority directions for future research.
6. The incorporation of automotive end-of-life rubber waste into particleboard at 10% vol. provides a quantifiable acoustic benefit while contributing to waste valorization within a circular economy framework.
7. The modified composites demonstrate structural potential suitable for non-load-bearing partitions and interior cladding. However, further testing of long-term mechanical stability and formaldehyde emission is necessary before these materials can be fully qualified for structural use in the building sector.

REFERENCES

1. Hassan MR., Rodrigue D. Application of waste tire in construction: A road towards sustainability and circular economy. Sustainability. 2024; 16: 93852. https://doi.org/10.3390/su16093852
2. Wiśniewska P., Wójcik NA., Ryl J., Bogdanowicz R., Vahabi H., Formela K., Reza Saeb M. Rubber wastes recycling for developing advanced polymer composites: A warm handshake with sustainability. J. Clean. Prod. 2023; 139010. https://doi.org/10.1016/j.jclepro.2023.139010
3. Swift MJ., Bris P., Horoshenkov KV. Acoustic

absorption in re-cycled rubber granulate. Appl. Acoust. 1999; 56(3–4): 203–212. https://doi.org/10.1016/S0003-682X(98)00061-9

4. Xu X., Wang H., Sun Y., Han J., Huang R. Sound absorbing properties of perforated composite panels of recycled rubber, fiberboard sawdust, and high density polyethylene. J. Clean. Prod. 2018; 182: 567–573. https://doi.org/10.1016/j.jclepro.2018.03.174
5. Sienkiewicz M., Janik H., Borzędowska-Labuda K., Kucińska-Lipka J. Environmentally friendly polymer-rubber composites obtained from waste tyres: A review. J. Clean. Prod. 2017; 147: 560–571. https://doi.org/10.1016/j.jclepro.2017.01.121
6. Benazzouk A., Douzane O., Mezreb K., Quéneudec M. Physico-mechanical properties of aerated cement composites containing shredded rubber waste. Cem. Concr. Compos. 2006; 28(7): 650–657. https://doi.org/10.1016/j.cemconcomp.2006.05.006
7. Sukontasukkul P. Use of crumb rubber to improve thermal and sound properties of pre-cast concrete panel. Constr. Build. Mater. 2009; 23(2): 1084–1092. https://doi.org/10.1016/j.conbuildmat.2008.05.021
8. Maderuelo-Sanz R., Nadal-Gisbert A., Crespo-Amorós JE., Parres-García F. Acoustical performance of porous absorber made from recycled rubber and polyurethane resin. Latin Am. J. Solids Struct. 2013; 10(3): 585–600. https://doi.org/10.1590/S1679-78252013000300008
9. Ružickij R., Astrauskas T., Valtere S., Grubliauskas R. Sound absorption properties evaluation and analysis of recycled tyre textile fibre waste. Environ. Clim. Technol. 2020; 24(1): 221–233. https://doi.org/10.2478/rtuect-2020-0106
10. Ghofrani M., Ashori A., Rezvani MH., Ghamsari FA. Acoustical properties of plywood/waste tire rubber composite panels. Measurement. 2016; 94: 382–387. https://doi.org/10.1016/j.measurement.2016.08.020
11. Daeipor Z., Safdari V., Nurbakhsh A. Evaluation of the acoustic properties of wood–plastic–chalk composites. Eng. Technol. Appl. Sci. Res. 2017; 7(5): 2067–2071. https://doi.org/10.48084/etasr.830
12. Danihelová A., Sčensný P., Gergeľ T., Ondrejka V., Němec M., Igaz R., Štefko J., Mitterová I. Influence of flame retardant impregnation on acoustic and thermophysical properties of recycled technical textiles with the potential for use in wooden buildings. Polymers. 2021; 13(16): 2598. https://doi.org/10.3390/polym13162598
13. Badida M., Andrejiova M., Pinosova M., Moravec M. Acoustic analysis of soundproofing materials using recycled rubber from automobiles. Materials. 2025; 18(13): 3144. https://doi.org/10.3390/ma18133144
14. Kumar A., Choudhary V., Khanna R. Recycling polymeric waste from electronic and automotive sectors into value added products. Front. Environ. Sci. Eng. 2017; 11: 5. https://doi.org/10.1007/s11783-017-0991-x.
15. Szul T., Čabalová I., Tiwari R., Łyszczarz P. Właściwości termofizyczne i akustyczne płyt kompozytowych zawierających polimery odpadowe z izolacji kabli elektroenergetycznych. Przegl. Elektrotechn. 2025; 101(3): 28–33. https://doi.org/10.15199/48.2025.03.28
16. Bharathi M., Karthikeyan S., Sankar I., Siva I. Acoustic properties of PVC core natural fiber sandwich structure. AIP Conf. Proc. 2024; 2999: 020012. https://doi.org/10.1063/5.0225444
17. ISO 10534-2. Acoustics – Determination of acoustic properties in impedance tubes – Part 2: Transfer-function method. Geneva: International Organization for Standardization; 2023.
18. ISO 354:2003. Acoustics – Measurement of sound absorption in a reverberation room. Geneva: International Organization for Standardization; 2003.
19. PN-EN ISO 11654:1999. Akustyka – Wyroby dźwiękochłonne używane w budownictwie – Wskaźnik pochłaniania dźwięku. Warszawa: Polski Komitet Normalizacyjny; 1999.
20. ASTM C423-23. Standard test method for sound absorption and sound absorption coefficients by the reverberation room method. West Conshohocken, PA: ASTM International; 2023.
21. Grochowina MA., Leniowska L. Heuristic optimization of layered sound-absorbing structures using genetic algorithms. Adv. Sci. Technol. Res. J. 2025; 19(11): 329–337. https://doi.org/10.12913/22998624/129253
22. Ayrilmis N., Buyuksari U., Avci E. Utilization of waste tire rubber in manufacture of oriented strandboard. Waste Manag. 2009; 29(9): 2553–2557. https://doi.org/10.1016/j.wasman.2009.04.007