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The natural fibre composites and their acoustical performance

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ABSTRACT

This study investigates the microstructure and acoustical performance of eco-friendly epoxy–wood composites and plant fiber based materials for potential application as sound absorbing solutions. Natural fibers and wood-based composites are being increasingly used rather than synthetic fibers. This is due to their advantageous specific characteristics. They are low in cost (because they ofen are waste in production processes), environmentally friendly, non-toxic, renewable, and biodegradable, as well as abundant in supply. For research purposes, epoxy composites were manufactured with varying oak chips using controlled proportions of resin filler and their internal structure was characterised by industrial computed tomography (CT). The sound absorption coefficient (SAC) was determined using an impedance tube in the frequency range of 100–5700 Hz. The results showed that the acoustic properties strongly depend on the concentration of filler and microstructural uniformity. The highest and most stable absorption values, with coefficients approaching $\alpha \approx 1.0$ in the mid- and high-frequency ranges, were obtained for samples containing 65–75% wood chips. With a higher filler content, one can notice an increased heterogeneity of the structure, which directly affects the worsening of the reduction of sound absorption. Results confirm that the SAC coefficient is strongly dependent on the effective porosity and pore uniformity, and that the technological process of filling is of significant importance. Furthermore, the findings confirm that both epoxy–wood composites and plant fiber based materials demonstrate great potential as reproducible, wideband sound and eco-friendly absorbers.

Keywords: natural composites, plant fibers, sound absorption, computed tomography, impedance tube.

INTRODUCTION

With the ongoing development of industry, increasing attention is being paid to environmental protection and the rational management of waste generated in production processes. In recent years, natural fibers have gained preference over synthetic alternatives such as carbon or glass fibers in the development of sound-absorbing materials. Their inherent viscoelastic behavior and hollow cellular structure not only facilitate ease of processing but also enhance their acoustic insulation properties. Natural fibers are renewable resources that can be found in nature. Plant-based fibers have become the most popular among these fibers and have a significant market value. Among natural fibers, coir [1, 2], kenaf [3], hemp [4], sugarcane [5] and wood fibers, including softwood [6] and hardwood [7] are widely utilized due to their superior sound absorption capacity compared to conventional synthetic fibers. These materials are incorporated into a variety of acoustic products, including sound boards, protective glazing, and acoustic panels. The sound absorption coefficient of natural fibers is influenced by multiple factors, such as fiber morphology (e.g., diameter and thickness), frequency of the incident sound, and fiber type. According to the principles of sustainable development and the concept of ecologistics, developed countries strive to minimise waste production and maximize the reuse of materials [8]. The cutting and machining processes generate substantial amounts of wood chips and sawdust, which are most commonly treated as waste and used primarily as fuel in the form of briquettes [9].

Taking into account that one significant issue concerns waste produced during material processing, particularly components of organic origin such as wood, there is a growing interest in materials that, in addition to offering structural or decorative functions, also exhibit functional properties, such as enhancing the acoustic comfort of interior spaces.

One of the key parameters in this context is the sound absorption coefficient (SAC), which defines the ability of a material to dampen acoustic waves [10]. SAC is defined as the proportion of incident acoustic energy absorbed by the material in relation to the total incoming energy and is represented by α. It assumes values within the range of 0.00 to 1.00. If the acoustic energy can be fully absorbed, then $\alpha = 1$. An important characteristic of the SAC coefficient is its close relationship with both the frequency of sound and the direction of its propagation. It uses the average sound absorption value in all directions, and the frequencies of the absorbed sound must be clearly defined. This means that materials absorption capability is frequency-dependent and generally increases with rising frequency.

Composites are complex structured materials composed of at least two distinct phases, a matrix and a reinforcing phase, whose combination results in superior properties compared to those of the individual constituents. As a result, composites can offer high strength, stiffness, corrosion resistance, and fatigue durability, while maintaining a low mass. The literature presents various proposals for the reuse of waste materials, including used car tyres and rubber waste, as additives in construction materials to improve their vibration isolation properties [11]. Research into the use of natural fibers as sound-absorbing materials is generating considerable interest [5]. Composites made from these fibers demonstrate increasing SAC with rising frequency and sample thickness. Moreover, the introduction of an air gap behind the material significantly improves its performance in absorbing low-frequency sounds. Several studies have investigated the use of plant fibres and natural composites as sound-absorbing materials. Gholampour, A. and Ozbakkaloglu [12] and Liang et al. [13] provided a comprehensive review of synthetic and natural materials for the reduction of industrial noise.

The production of composites based on fibers typically involves biodegradable resins. These resins are polymers that can be derived from plant sources (e.g., starch and cellulose) or synthesized via the polymerization of sugars and vegetable oils, such as polylactic acid (PLA), polyethylene terephthalate (PET), and polypropylene (PP). Research findings indicate the high potential of these fibers for acoustic applications while maintaining the ecological integrity of the material.

The mechanism of sound absorption is influenced by a range of parameters, which can be broadly divided into two categories: material properties and sample preparation factors. The first category includes mainly the acoustic absorption coefficient of the base and additive materials.

The second category, i.e. sample preparation, encompasses macroscopic related variables such as material thickness, single- or multilayer configuration, surface preparation, the manufacturing methods, morphological features of the reinforcing components (size and shape), as well as fibre orientation (parallel, vertical, or random).

Effective noise control in all areas of engineering is essential. The development of acoustic materials with high noise absorption efficiency is a crucial area of research for both acousticians and architects in the acoustics industry. This study examines the potential for sound absorption by natural materials like Oak wood chips or sawdust and assesses how well they perform acoustically. The aim of this study is to examine the properties of selected eco-materials in terms of their potential application as sound absorbing materials to address the increasing demand to use eco-friendly natural fibers in different applications. These investigations have resulted in the development of several kind of materials with reliable and high functional performance in area of sound absorbing properties.

MATERIALS AND METHODS

The sound absorption coefficient is one of the most widely employed parameters for assessing the acoustic performance of sound-absorbing materials. According to EN ISO 354:2005, it is determined through standardized measurement and computational procedures carried out in a reverberation chamber under diffuse field conditions, typically using impulse excitation methods. In this approach, test specimens usually cover an area of approximately 10–12 m^2, while the reverberation chamber volume is on the order of 200 m^3. An alternative technique for evaluating the coefficient, particularly as a function of the angle of incidence, utilizes smaller samples examined within a standing wave field inside the impedance tube This method enables precise characterization of angular dependence of sound absorption and it will be used in this paper. Both approaches generally provide reliable results within the frequency range extending up to 5.000 Hz. The samples were prepared using the materials characterized in the Tables 1 and 2.

The oak wood chips used as filler were obtained as a by product from the parquet manufacturing process. Therefore, the applied material represents post production waste, according to the study's focus on sustainable use of resources. Importantly, oak wood met the requirements of PN-EN 13226:2020-07 [14], which specifies that parquet elements must have a moisture content in the range of 7–11%. Compliance with this standard ensured the dimensional stability of the filler and proper adhesion to the epoxy resin matrix.

To ensure the repeatability of sample shapes, cylindrical molds with a diameter of 34.25 mm were designed and fabricated using 3D printing technology from PET-G material. This material ensured the molds were leak proof and chemically inert with respect to the resin components. To prevent deformation during the curing process, the molds were placed within an additional plaster structure, which stabilized their shape and prevented bulging. The composition of each sample was prepared using an A&D INSTRUMENTS LTD. GH-300-EC laboratory balance, which allowed precise measurement of the resin and wood chip components according to the assumed filler content variants. Composite samples were prepared based on specific weight concentrations of components. Each mixture was designed to achieve a total target mass of 100 g (excluding the hardener). For the reference sample (100% resin), 100 g of epoxy resin and 1 g of hardener were used, as per the manufacturer's recommendation. For samples containing wood chips, component proportions were adjusted accordingly. For instance, for a 50% filler concentration, 50 g of chips and 50 g of resin were used, and the amount of hardener was scaled proportionally to the resin mass (0.5 g). This approach allowed the preparation of a series of samples with varying filler phase content while maintaining consistent processing conditions. The prepared mixtures were poured into the designated molds placed in the plaster casing. Three samples were prepared for each filler content variant. As a result, a series of samples was obtained with the required weight concentrations of components. Table 3 contain information on the specifications of the tested composite samples. The filler concentration range (0–40 wt%) was selected based on both practical and scientific considerations. Previous studies have shown that an excessive content of wood or fibre can hinder resin impregnation and result in large pores or voids, thus decreasing both mechanical and acoustic performance of composites [1]. Therefore, the chosen concentration range ensured both technological feasibility and comparability with other

Table 1. Characteristics of binders

Material name	Chemical composition	Application
Epoxy resin	– Styrene – Phthalic anhydride – Maleic anhydride – Epoxy resin (reaction product of bisphenol A and epichlorohydrin; average molecular weight ≤ 700)	Used in the automotive industry
Hardener (BPO)	– Benzoyl peroxide – Dibutyl phthalate – Amorphous silica – Dye – Inhibitors	Initiates the curing process of polyester resins through polymerization

Table 2. Physical parameters of the filling

Wood species	Fraction size [mm]	Density [kg/m³]	Humidity [%]	Material
Oak wood	5–30	~ 180–250	7–11%	

Table 3. Material proportions in samples

Sample no.	Resin concentration [%]	Wood chips weight [g]	Resin weight [g]
1.	100	0	100
2.	95	5	95
3.	90	10	90
4.	85	15	85
5.	80	20	80
6.	75	25	75
7.	70	30	70
8.	65	35	65
9.	60	40	60

experimental studies on bio-based composites. The curing process was carried out at room temperature and lasted for a minimum of 24 hours, according to the resin manufacturer's guidelines. Upon completion of curing, the samples were subjected to mechanical processing using a lathe; each sample was trimmed to a uniform length, and the frontal surface was planed using a lathe knife to ensure consistent conditions for subsequent testing. In sound absorption investigations, one of the significant determinants of a material's effectiveness is its thickness. There is a clear correlation between sound absorption and material thickness, particularly in the low frequency ranges. In our tests, we varied the granulation and concentration while maintaining the same sample thickness. Whereas the diameter of the samples was determined by the diameter of the impedance tube. As a result, the test sample had a cylindrical geometry with dimensions of 34.25 mm in diameter and 45 mm in length.

METHODOLOGY

The first stage of the analysis of the prepared samples involved the evaluation of their internal structure using computed tomography (CT). The examination was conducted using an industrial X-ray computed tomography system, the phoenix v|tome|x s, originally developed by General Electric (GE) and currently offered by Waygate Technologies. The system is equipped with two X-ray tubes, enabling scanning in both macro and micro modes, and delivering high-resolution images. A directional microfocus X-ray tube with parameters of 240 kV / 320 W was used, allowing for the acquisition of detailed image data. Image capture was carried out using a DXR250RT flat-panel detector made of amorphous silicon, featuring a resolution of 1024 × 1024 pixels and a pixel size of 200 μm. The detector operates in 14-bit mode, allowing for the registration of over 65,000 grayscale levels.

It is worth noting that there is no unified standard defining scanning parameters for this type of material each sample requires individually adjusted settings based on histogram analysis [15]. During scan setup, current and voltage levels were adjusted to ensure that the grayscale value characteristic for the sample was at least 200, and the maximum grayscale level of the background did not exceed 10.000. Moreover, the grayscale ratio between the background and the sample had to remain within the range of 2–20, guaranteeing adequate contrast and image clarity.

During the scanning process, each sample was exposed to system CT phoenix v|tomex|s Producent GE (General Electric) projections, enabling detailed imaging of wood chip distribution within the resin volume, as well as the identification of potential defects, such as air voids, material inhomogeneities, or phase separation. The acquired image data were further analyzed using dedicated digital software, which allowed for evaluation of structural uniformity and estimation of the filler's volumetric content. These analyses aimed to verify the adequacy of the mixing process and the quality of the fabricated samples.

Experimental investigations involving the measurement of SAC were carried out at the Laboratory for Acoustic Phenomena Modelling at the University of Rzeszow [16]. To determine SAC, an impedance tube manufactured by Siemens (model: Mecanum Inc., S/N: 2444-408) was used. A schematic diagram of the impedance tube setup is shown in Figure 1. The measurement system was operated in accordance with applicable standards: PN-EN ISO 10534-2:2003, ASTM

E-1050, and ASTM E-2611 (Transmission Loss) [17–19]. The measurement station and equipment were identical to those described by the authors in [15]. The laboratory setup included a Siemens Mecanum Inc. impedance tube, a Siemens LMS SCADAS Mobile analyzer, a computer with Simcenter Testlab software, and PCB measurement microphones (type 378A14, 1/4″), positioned at 65 mm for low frequencies and 29 mm for high frequencies. The measurements covered a wide frequency range. The microphones were verified prior to testing, and a calibration test was performed using a calibrator set to 114 dB at 1000 Hz. The SAC was determined based on averaged results over the frequency range from 100 to 5700 Hz. All measurements were performed under standard laboratory conditions, at a temperature of 20 °C and atmospheric pressure of 1015 hPa.

RESULTS

The studies conducted using industrial X-ray computed tomography (micro-CT) enabled a detailed evaluation of the internal structure of composites composed of epoxy resin and oak wood chips. The obtained images including cross sectional and longitudinal slices as well as 3D reconstructions provided valuable insights into the spatial distribution of individual components within the material and revealed the presence of defects such as micropores or air voids (Figure 2). The

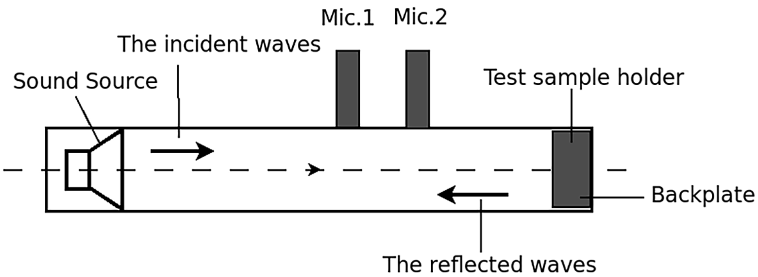

Figure 1. A schematic diagram of the impedance tube setup

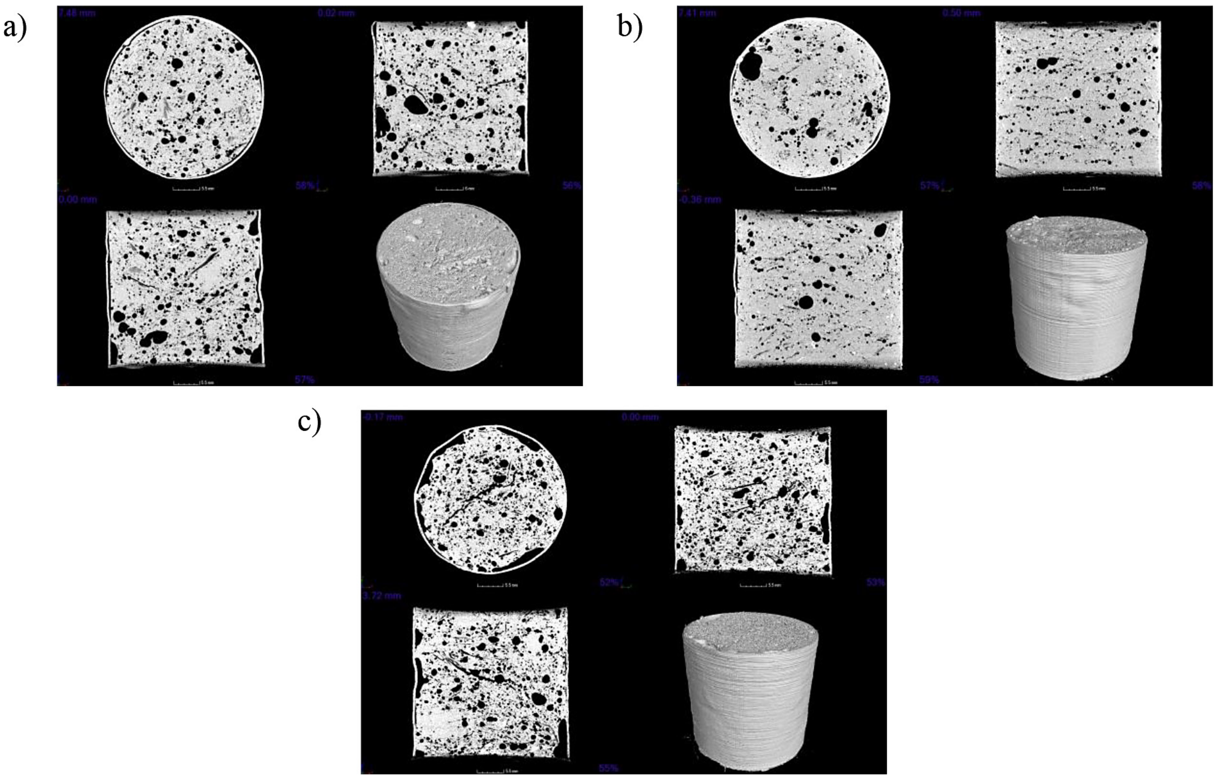

Figure 2. Images of composites with 90% resin content, X-rayed with tomography: (a) sample I, (b) sample II, (c) sample III

acoustic performance of the samples was assessed using an impedance tube, which allows for precise determination of the material’s SAC as a function of frequency. This method enables the evaluation of the acoustic properties of the specimens, particularly their ability to absorb acoustic wave energy across different frequency ranges. The measurements produced graphical results in which the X axis represents the frequency of the acoustic signal (expressed in Hz), while the Y axis shows the SAC values, ranging from 0 to 1. A value of 0 indicates total reflection of the sound wave, whereas a value of 1 corresponds to complete absorption of the acoustic energy by the sample. Interpretation of the resulting graphs makes it possible to identify the frequency range in which a given material most effectively attenuates sound information that is particularly important in the design of soundproofing materials, such as those used in acoustic insulation, building partitions, or interior finishing elements. Furthermore, analysis of the results may reveal a correlation between the internal structure of the material and its effectiveness in sound absorption. When combined with data obtained from computed tomography, this enables a more comprehensive evaluation of the functional properties of the studied composites (Figures 3–11) [20].

Analysis of the results obtained by tomographic imaging

The analysis conducted using X-ray computed tomography revealed significant differences in the internal structure of the examined samples. In the case of the first sample, an irregular, chaotic

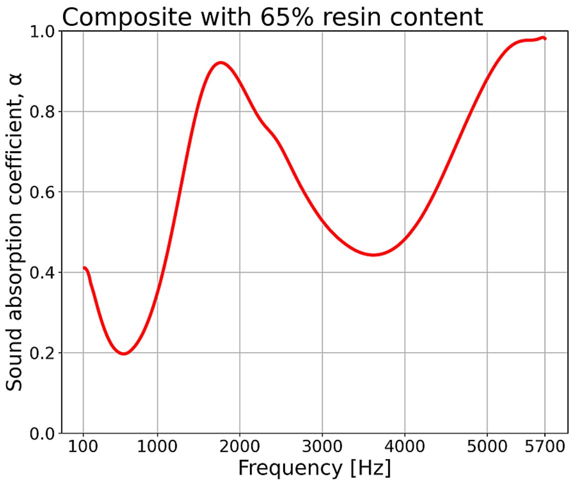

Figure 4. Sound absorption coefficient for the sample with 65% resin content

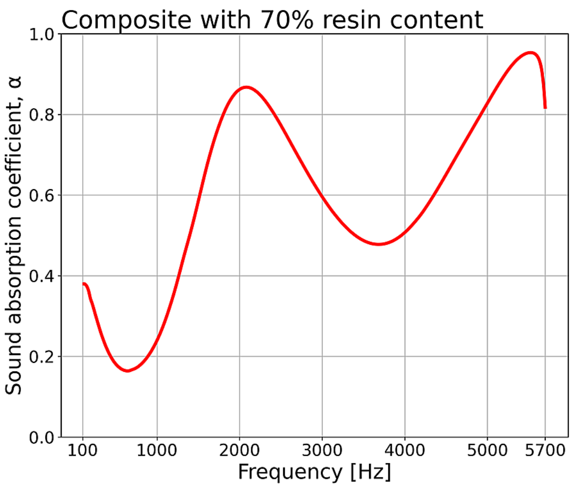

Figure 5. Sound absorption coefficient for the sample with 70% resin content

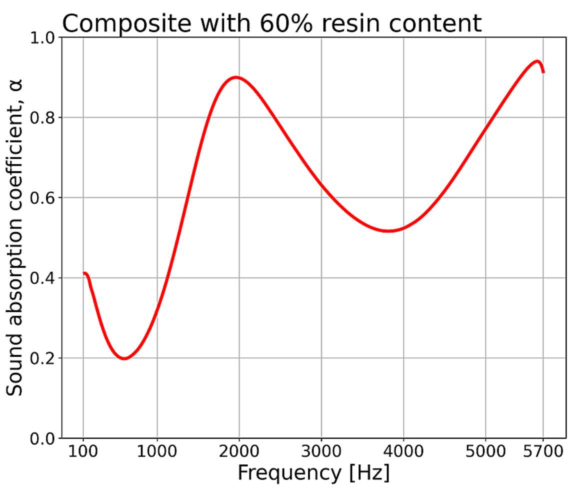

Figure 3. Sound absorption coefficient for the sample with 60% resin content

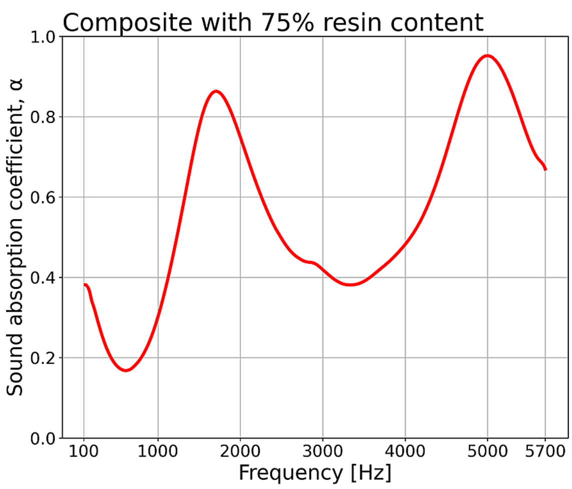

Figure 6. Sound absorption coefficient for the sample with 75% resin content

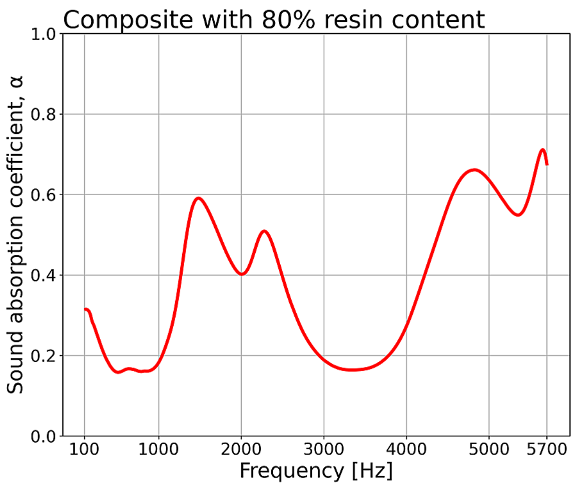

Figure 7. Sound absorption coefficient for the sample with 80% resin content

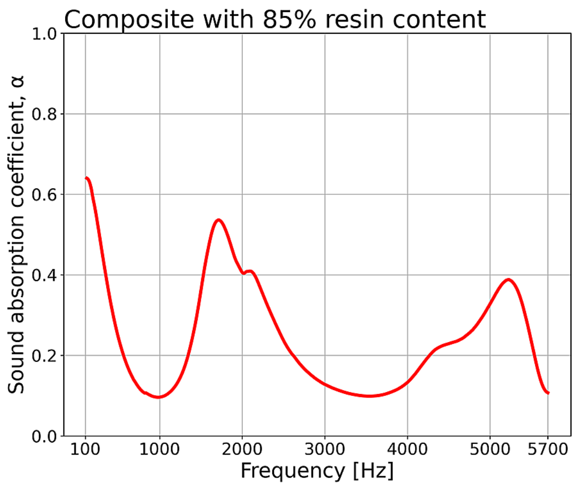

Figure 8. Sound absorption coefficient for the sample with 85% resin content

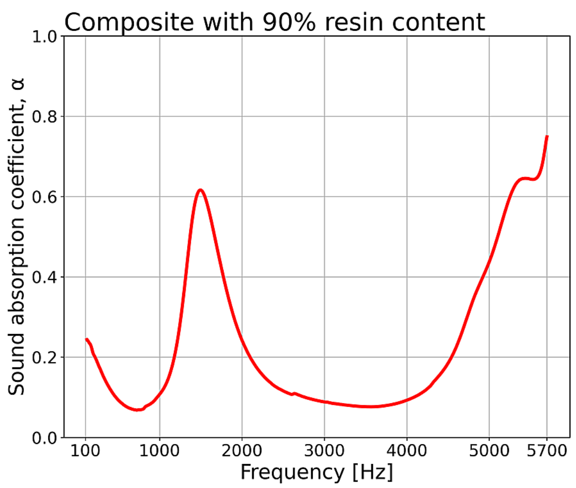

Figure 9. Sound absorption coefficient for the sample with 90% resin content

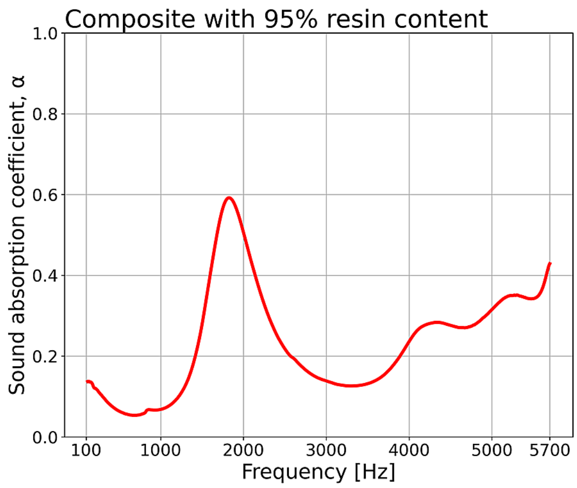

Figure 10. Sound absorption coefficient for the sample with 95% resin content

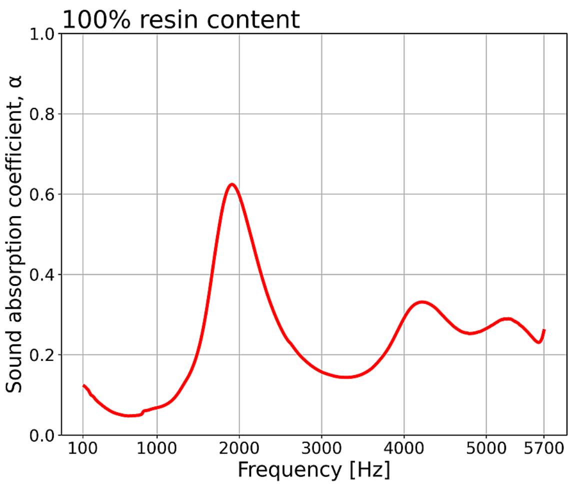

Figure 11. Sound absorption coefficient for the sample with 100% resin content

distribution of wood chips was observed, with no clear orientation or alignment. Numerous pores of varying sizes were randomly distributed throughout the material. Such a structure may indicate specific characteristics of the mixing process, during which air could have been secondarily introduced into the system. Additionally, the lack of an effective degassing method such as vacuum processing may have contributed to the entrapment of air bubbles during the resin curing stage. The presence of pores and structural heterogeneity may negatively affect the mechanical properties of the composite, including its strength, stiffness, and resistance to variable operating conditions.

The second sample exhibited a different type of porosity. The pores were noticeably larger than those in the first sample but occurred less frequently and were mainly concentrated in specific areas particularly where the wood chips were more densely packed. This distribution suggests non uniform resin flow during the molding process. Local agglomerations of wood particles may have obstructed resin infiltration, leading to poorly impregnated zones and the formation of larger voids. This implies that porosity results not only from the mixing process but also from local disturbances in the resin flow and its humidity in relation to the wood surfaces.

The third sample demonstrated a significantly more homogeneous structure. The pores were much smaller and uniformly distributed throughout the volume, and the arrangement of wood chips appeared more ordered and compact. This effect may result from a more efficient mixing process, which ensured better dispersion of chips within the resin matrix, along with more effective degassing before curing. The homogeneity of the structure and the reduced number of defects indicate good impregnation of wood particles by the resin, which contributes to improved mechanical and physical properties of the material. This type of internal structure may also positively influence the composite's behavior in applications requiring dimensional stability or dynamic response such as acoustic insulation.

The tomographic image analysis of all three samples confirms that the quality of the composite is influenced not only by the choice of components but, above all, by the technological process itself. The method of introducing wood chips into the resin, the degassing technique (e.g., vacuum mixing), as well as the temperature and pressure conditions during curing, play a fundamental role in shaping the final microstructure. Even with an identical quantitative composition of components, variations in production procedures may lead to markedly different outcomes in terms of structural homogeneity, defect type and distribution, and consequently, differences in strength, durability, and performance predictability under real world conditions.

Future research should not only focus on microstructural analysis but also investigate correlations between visible defects and the mechanical properties of the samples. An important direction for further development is the identification of optimal processing parameters that would result in minimal porosity and high structural uniformity. The use of controlled mixing and degassing conditions, along with process automation, could significantly improve the quality and repeatability of wood–epoxy composite production.

Analysis of the SAC measurements

Based on the measurements of the SAC (α) as a function of frequency for samples containing varying percentages of wood chips, a significant influence of the mixture composition on the acoustic properties of the material was observed. The wood chip content ranging from 60% to 100% notably altered the acoustic absorption characteristics within the tested frequency range (100–5700 Hz). Samples with lower wood chip content (60% to 70%) exhibited the highest absorption coefficients. In particular, samples with 65% and 70% wood content showed α values close to 1.0 in the mid and high frequency ranges, indicating excellent sound absorbing properties. The homogeneous structure of these composites resulting from an optimal resin to chip ratio promoted effective diffusion and scattering of sound waves. For samples with wood chip contents between 75% and 85%, a different pattern emerged. Although the absorption coefficient remained relatively high, distinct resonance peaks appeared. These materials absorbed sound effectively only within specific frequency bands, which may be attributed to a more porous and less uniform internal structure. The higher wood content likely led to the formation of air channels and voids that resonated at particular frequencies. At wood chip contents above 85% especially in the 90%, 95%, and 100% samples a noticeable decrease in α values was observed. Sound absorption became less effective, and the maximum absorption values shifted toward lower frequencies. These values were also significantly lower compared to samples with less wood content. This phenomenon may be explained by the limited amount of resin, which at lower ratios was insufficient to properly bind the material's structure, thereby reducing its ability to absorb and scatter sound waves. The optimal wood chip content for achieving the best sound absorbing properties lies within the range of 65% to 75%. In this range, the materials exhibited high and consistent absorption coefficients across a wide frequency band. Too little or too much wood content led to deterioration in the acoustic performance of the material.

In the case of samples with a 90% resin content, CT imaging revealed visible differences in internal structure, despite their identical quantitative composition. These variations were mainly related to the distribution of pores and wood chips. However, the measured sound absorption curves for these samples remained generally consistent and only minor local deviations could be noticed. This suggests that structural heterogeneity may influence the acoustic response, although in our study the observed effect was not pronounced.

The combined CT and SAC analyses demonstrate that the acoustic performance of the composites is directly related to their microstructural characteristics. Samples with a uniform distribution of wood chips and relatively small and evenly distributed porosity (65% to 70% filler content) exhibited broadband and high absorption, with α values approaching 1.0 at mid-and high frequencies. On the contrary, composites with higher wood chip content revealed the formation of larger voids and air channels, resulting in resonant peaks and selective absorption at specific frequencies. This indicates that microstructural uniformity and controlled porosity are critical parameters for achieving stable and wide-range sound absorption properties.

CONCLUSIONS

The conducted study enabled a comprehensive evaluation of epoxy-wood composites in terms of both their internal microstructure (via computed tomography) and acoustic performance (using an impedance tube). The CT analysis revealed that, despite identical component ratios, the internal structures of the samples differed significantly depending on the preparation method. This highlights the critical importance of process parameters such as mixing, degassing, and resin impregnation. The sample with the most homogeneous structure exhibited the fewest defects and the highest mechanical potential.

Acoustic testing showed that the best sound absorption properties were achieved in samples containing 65–75% wood chips. Within this range, high and stable SAC were recorded across a broad frequency spectrum. Both lower and higher filler contents led to reduced acoustic efficiency.

In conclusion, the quality of the composite depends not only on the ratio of its components but, above all, on the precise control of the manufacturing process. Optimizing technological parameters is essential for obtaining a material with reliable and high functional performance. Importantly, the study showed a correlation between the microstructure and the acoustic absorption properties of the composites. Homogeneous structures with fine and uniformly distributed pores provided a wide bandwidth and high absorption coefficients (up to α ≈ 1.0 for 65–70% filler content), while heterogeneous structures with agglomerates and channel voids promoted resonance phenomena and reduced overall absorption efficiency. These results confirm that the SAC coefficient is strongly dependent on the effective porosity (Φ) and pore uniformity, and that the technological process of filling is of significant importance. However, it is undoubtedly true that achieving eco-friendly and high functional performance in the area of sound-absorbing properties of the considered composites, created from waste materials such as chips or sawdust, is fully justified.

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