Sound Absorption Efficiency of Plywood-Carbon Fiber Composites: A New Frontier in Wood Material Science

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The objective of this study was to investigate the sound absorption efficiency of plywood-carbon fiber composite materials and evaluate their potential as acoustic panels. In this work, plywood and plywood-carbon fiber composite materials were produced using Uludağ fir (*Abies nordmanniana* subsp. *bornmülleriana* Mattf.) peeling veneer, woven carbon fiber, and polyvinyl acetate (PVAc) adhesive. Three experimental groups and a control group were created. The materials from plywood-carbon fiber composite were manufactured in three different designs to form experimental groups. The sound absorption coefficients of the plywood and the composite materials were tested *via* the impedance tube method, according to ASTM standard E1050-98 (2006). Attention was paid to the acoustic behavior at low (bass) frequencies (63 Hz to 250 Hz), mid frequencies (315 Hz to 1600 Hz), and high (treble) frequencies (2000 Hz to 6300 Hz). It was determined that the plywood-carbon fiber composite materials could reflect or transmit sound waves at low (bass) frequencies, while significantly absorbing sound waves at high (treble) frequencies. It can be suggested that plywood-carbon fiber composite materials could be used as sound absorbing acoustic panels.

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INTRODUCTION

Laminated wood composites (LWC) occupy a significant position within the field of construction materials. Their popularity is largely due to their exceptional characteristics in terms of lightness, durability, and aesthetic appeal. Wood is an environmentally friendly option due to its status as a sustainable material derived from renewable resources. However, the natural weaknesses of wood can impose limitations, particularly in terms of strength and durability. To address these limitations, hybrid composites are produced by combining different materials. The increasing demand for sustainable, lightweight, and high-performance materials in various industries has led to a growing interest in Reinforced Laminated Wood Composites (RLWC). These materials not only offer ecological advantages due to their renewable nature but also possess excellent mechanical properties, making them highly suitable for a wide range of structural and non-structural applications. Among these, one of the most promising applications is their use as sound-absorbing panel boards, which is critical in addressing noise pollution and improving acoustic environments in both residential and industrial settings.

The demand for wood and wood-based materials is on the rise with the progression of time. Technological advancement and an escalation in the industrialization rate have led to an expansion in the range of applications for wood-based materials. LWC constitutes a specific category of structural composite timber. The history of veneers, which form the basis of wood-based building materials, can be traced back to the period of the Pharaohs. The technique of obtaining a peeling veneer from logs was discovered in 1890 and subsequently produced in wide boards. LWC was first employed in the manufacture of propellers for fighter aircraft during the Second World War. From the mid-1970s onwards, it has been an important wood-based composite material (Dallı 2005).

Laminated wood composites are typically manufactured from low-density and low-economic-value tree species, which results in physical properties that are not optimal. The utilization of high-density and economically valuable tree species increases the cost and is not a preferred approach, as it leads to a reduction in forest resources. Consequently, wood-based materials require a reinforced design to compensate for these inherent limitations.

Carbon fiber is a material that is widely used in laminated wood composites due to its high strength and low density. The combination of carbon fiber and wood results in an improvement in the mechanical and physical properties of the composite, thereby enabling its use in a diverse range of applications (Auriga *et al.* 2020). Nevertheless, the acoustic properties of such hybrid composites, particularly regarding sound absorption performance, represent a field that remains to be investigated in greater detail.

The most significant acoustic characteristic of wood and wood-based materials is that, despite its lightweight nature, the speed at which sound waves propagate is relatively high. The wooden material structure enables the absorption and diffusion of sound. For this reason, wood material exhibits superior properties in comparison to other acoustic materials. Consequently, it is employed in the manufacture of musical instruments and is a common wall covering material used to provide acoustic comfort in theatres, concert halls, cinemas, and conference facilities. The impact of wood-based materials used in interior construction is significant in absorbing sound, regulating sound waves, and preventing unwanted sound echoes caused by the reflection of sound on walls (Berkel 1970).

Sound absorption performance is particularly important in environments where the control of reverberation and noise is essential, such as in buildings, automotive interiors, and public spaces. Reinforced laminated wood composites (RLWC), when designed as acoustic panels, can contribute to a more pleasant and healthier environment by reducing unwanted sound reflections and enhancing acoustic comfort. However, despite the potential benefits, the acoustic performance of such materials, particularly those reinforced with carbon fiber and wood veneer, remains underexplored in the literature. A thorough understanding of how these materials perform in sound absorption is crucial for optimizing their design and expanding their application scope.

The technological properties of laminated wood composites are undergoing a significant enhancement as a result of the reinforcing materials employed in the coating and lamination processes (Rowlands *et al.* 1986; Pidaparti and Johnson 1996; Hallstrom and Grenestedt 1997; Fiorelli and Dias 2006; Taheri *et al.* 2009; Basterra *et al.* 2012; Güler and Subaşı 2012; Ghofrani *et al.* 2016; Özyurt 2020; Núñez-Decap *et al.* 2023; Özyurt and Özdemir 2023; Ramkumar *et al.* 2024). In particular, innovative reinforcers, such as polymer-based resins and fiber-reinforced materials, render wood surfaces more durable and provide longevity. Furthermore, these materials enhance the resistance of wood to moisture, heat, and chemical effects, thereby expanding the performance and areas of use in laminated composites. Consequently, reinforced laminated wood composites are emerging as a high-performance, sustainable material option in the construction and furniture industry.

The aim of this study is to investigate the sound absorption performance of plywood-carbon fiber composite materials at low (bass), medium, and high (treble) frequencies (Hz). There is no comprehensive research in the literature on the acoustic properties of LWC produced using carbon fiber and fir peeling veneer. Consequently, this study makes a significant original scientific contribution to the field.

EXPERIMENTAL

Materials

In this study, Uludağ fir (*Abies nordmanniana* subsp. *bornmülleriana* Mattf.) peeling veneer, woven carbon fiber, and polyvinyl acetate (PVAc) adhesive were used. Uludağ fir veneer sheets with a thickness of 2.1 mm were used. The veneers were dried until the moisture content reached 7%. Only first-class veneer, knot-free, and crack-free veneer sheets were selected for the study. The woven carbon fiber fabric was utilized as the reinforcement material. Woven carbon fiber had a laminate thickness of 0.45 mm, carbon content in fiber of 95%, average density of 1.80 g/cm³, and weight of 300 g/m². Polyvinyl acetate (PVAc) adhesive was employed as the bonding agent, ensuring adequate adhesion between the layers of wood veneer and woven carbon fiber. Some properties of the polyvinyl acetate (PVAc) adhesive were as follows: specific gravity of 1.2 g/cm³ at a temperature of 21 °C, solid content of 58 ± 2%, pH of 5.5 to 7, viscosity of 18.00 ± 35.00 mPa·s. All of these materials were sourced from commercial suppliers based in Turkey.

Manufacture of LWC and Plywood-Carbon Fiber Composite Panels

The laminated wood composite (plywood) panels were produced using Uludağ fir peeling veneers and PVAc adhesive. The PVAc adhesive, with an average application amount of 230 g/m², was evenly applied to the veneer surfaces. Four groups of composite panels were created: one control group and three experimental (plywood-carbon fiber composite materials) groups (Fig. 1).

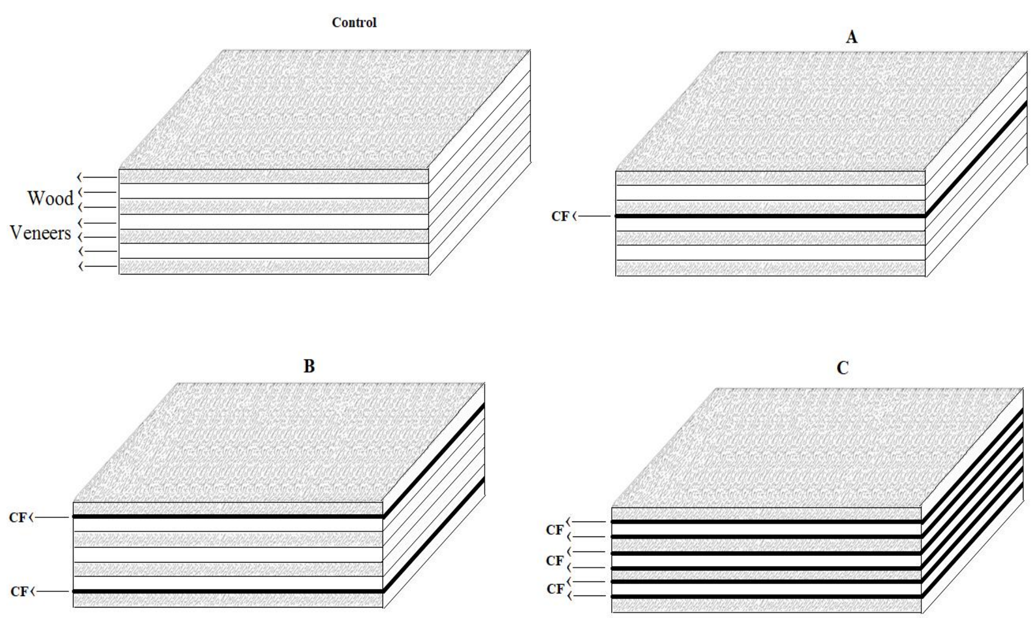

Fig. 1. Schematic image of the control and experimental groups (CF: Carbon fiber)

The control group was made entirely of Uludağ fir veneers bonded with PVAc adhesive and woven carbon fiber was not used. Carbon fiber was used in different adhesive layers of composite materials (experimental groups). The specific configurations were as follows: Carbon fiber in the third adhesive layer (Group A), carbon fiber in the first and sixth adhesive layers (Group B), and carbon fiber in all adhesive layers (Group C). The fir veneers were arranged in a seven-layer configuration (fiber directions perpendicular to each other), and the adhesive was applied between each veneer layer. The assembly was then pressed in a hot press at a temperature of 50 °C and a pressure of 7 kg/cm^2 to ensure proper bonding and lamination. After pressing, the laminated wood composite panels were removed from the press and allowed to cool. Fifteen plywood boards were produced for each group (LWC boards with 80 cm width, 80 cm length), totaling 60 laminated wood composite boards.

Acoustic Properties

The sound absorption coefficient (SAC) of the LWC produced in this study was measured using the Impedance Tube Method, following the ASTM E1050-98 (2006) standard. The composite panels were precisely cut into the required dimensions for testing using a Computer Numerical Control (CNC) machine to ensure accurate and consistent sample preparation. The test samples (control and experimental groups) were conditioned at a temperature of 20 °C ± 3 °C and a relative humidity of 65% ± 5% until a stable weight was reached (approximately 25 d). The impedance tube can measure low frequencies (63 to 1600 Hz) with a large diameter tube (99.8 mm) and high frequencies with a small diameter tube (29.95 mm). The acoustic performance of the LWC and plywood-carbon fiber composites across different frequency ranges low (bass), mid, and high (treble) frequencies were evaluated by measuring the SAC over a frequency range of 63 Hz to 6300 Hz. The measurements were carried out using an impedance tube setup, where the samples were exposed to incident sound waves, and the absorbed, transmitted, and reflected sound pressures were recorded to calculate the SAC values. Each composite sample was tested at least three times. This refers to the testing of ten different samples of the same formula, with the objective of ensuring reproducibility. By repeating the tests on distinct samples, the aim was to verify that the results were consistent across different specimens, thus ensuring the robustness and repeatability of the findings. The obtained SAC values were analyzed to assess the acoustic performance of the materials across the specified frequency range. Further, the SAC results were analyzed *via* ANOVA (Analysis of Variance) using the SPSS statistical software program (IBM, Version: 29.0.2, Armonk, NY, USA). In this study, the number of Carbon Fiber (CF) layers (0, 1, 2, and 6 for the Control, Group A, Group B, and Group C, respectively) served as the independent variable, while the sound absorption coefficient (SAC) at 1/3 octave frequencies (63 Hz to 6300 Hz) was the dependent variable. This distinction is critical for understanding the role of ANOVA in identifying whether the CF layer variations have a statistically significant effect on the SAC values across the tested frequency range.

RESULTS AND DISCUSSION

The results of the ANOVA in Table 1 show that the woven carbon fiber had significant (a p-value less than 0.001) effects on the SAC values.

Table 1. Average Values of SAC (63 Hz to 6300 Hz) and ANOVA Results (p-value <0.01)

Frequency (Hz)	Group				p-Value	Standard Deviation
	Control	A	B	C		
63	0.02	0.03	0.04	0.06	0.0000**	0.01
80	0.03	0.04	0.05	0.07	0.0000**	0.01
100	0.04	0.06	0.05	0.07	0.0000**	0.02
125	0.06	0.07	0.09	0.10	0.0000**	0.02
160	0.07	0.09	0.10	0.12	0.0000**	0.03
200	0.08	0.11	0.13	0.14	0.0000**	0.05
250	0.07	0.13	0.15	0.17	0.0000**	0.08
315	0.08	0.14	0.15	0.18	0.0000**	0.09
400	0.08	0.19	0.20	0.21	0.0000**	0.10
500	0.09	0.21	0.22	0.23	0.0000**	0.11
630	0.13	0.25	0.28	0.31	0.0000**	0.12
800	0.15	0.28	0.30	0.32	0.0000**	0.11
1000	0.18	0.30	0.32	0.36	0.0000**	0.13
1250	0.19	0.31	0.32	0.40	0.0000**	0.13
1600	0.19	0.36	0.39	0.45	0.0000**	0.14
2000	0.20	0.41	0.45	0.50	0.0000**	0.13
2500	0.20	0.43	0.48	0.53	0.0000**	0.15
3150	0.22	0.47	0.50	0.56	0.0000**	0.12
4000	0.21	0.52	0.54	0.60	0.0000**	0.16
5000	0.24	0.53	0.57	0.66	0.0000**	0.15
6300	0.26	0.56	0.60	0.70	0.0000**	0.14

A single star (*) represents p-values between 0.01 and 0.05. A double star (**) represents p-values less than 0.01.

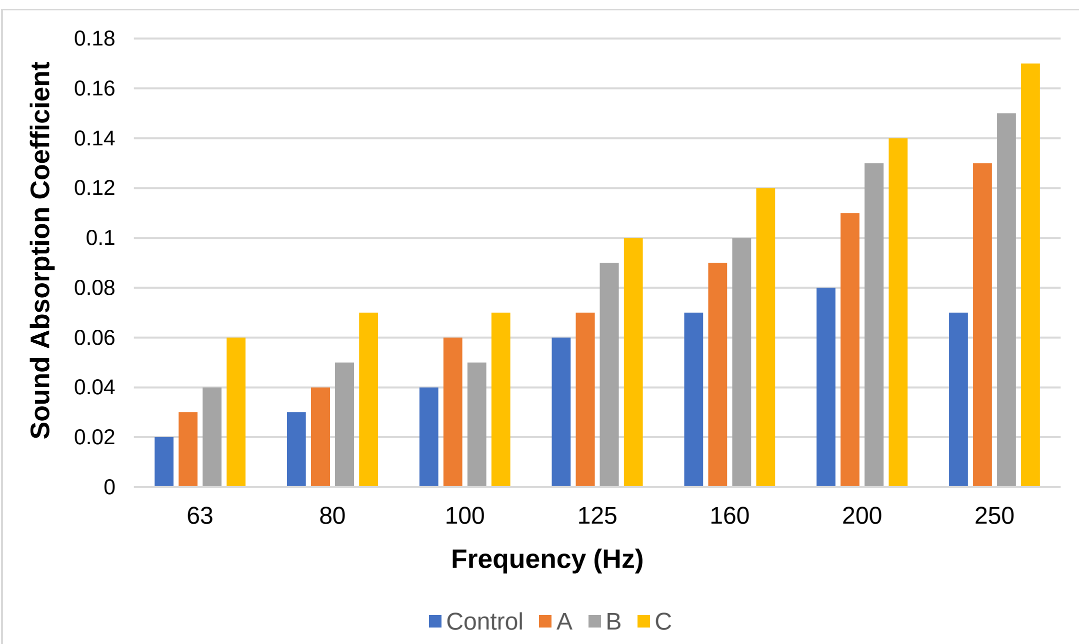

Fig. 2. Low (bass) frequency SAC values of the control A, B, and C groups

The values of the plywood-carbon fiber composite panels were higher than the SAC values of the control group. A direct relationship was observed between the increase in frequency and the enhancement in sound absorption coefficient. It was determined that the acoustic performances of the plywood-carbon fiber composites had improved. The acoustic performance of the produced composite materials at low (bass), medium, and high (treble) frequencies is presented in Figs. 2, 3, and 4, respectively.

Figure 2 indicates that the SAC values (the highest) for the control, A, B, and C groups within the 63 Hz to 250 Hz frequency range were measured as 0.07, 0.13, 0.15, and 0.17, respectively. These results indicate that the highest sound absorption performance was achieved by Group C. It is understood that the sound absorption performance of plywood-carbon fiber composite materials at low (bass) frequencies is not sufficient. It was determined that the composite materials (control and experimental groups) reflect or transmit a significant portion of sound waves at low (bass) frequencies.

Low (bass) frequency sound waves have longer wavelengths and generally require thicker, more porous, or flexible materials to be effectively absorbed. Fir veneer and woven carbon fiber fabric, while providing strength and rigidity to the composite, are likely to exhibit relatively high stiffness and low porosity. These characteristics limit their ability to dissipate the energy of lower frequency sound waves through friction or internal damping. Additionally, the laminated structure may lack the necessary thickness or compliance to induce sufficient air movement or create resonant cavities that enhance low-frequency absorption. To enhance the low (bass) frequency absorption characteristics, several strategies could be considered in future work. For instance, increasing the composite thickness could create a deeper structure that absorbs more sound in the bass range. Additionally, integrating perforated or porous designs, or combining the composite with other damping materials such as rubber or polyurethane foam, could significantly improve low-frequency sound absorption.

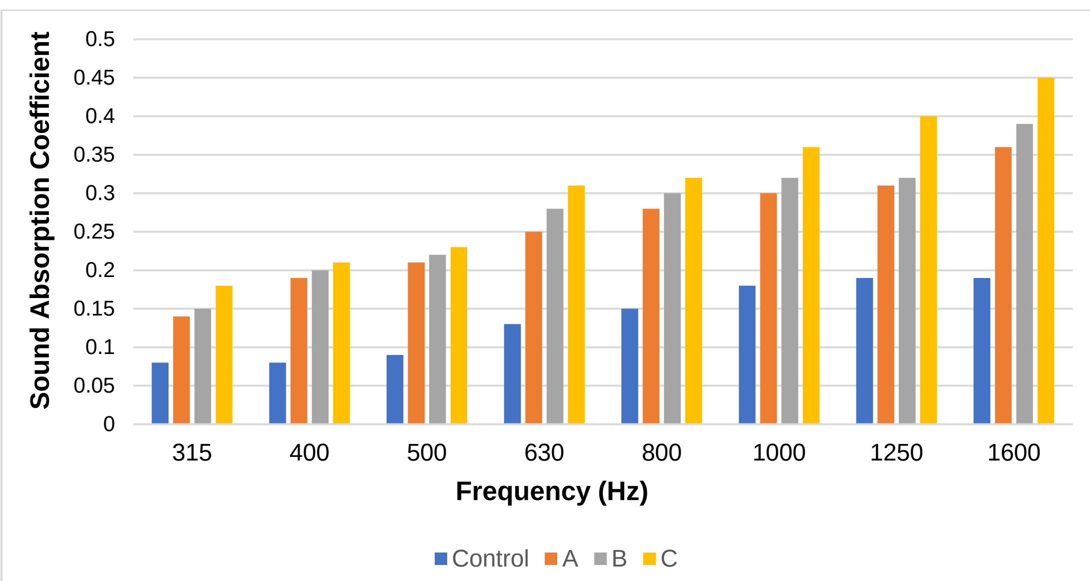

Fig. 3. Middle frequency SAC values of the control A, B, and C groups

In the literature, research on the sound absorption performance of carbon fiber materials at low (bass) frequencies has shown that these materials largely transmit or reflect sound waves (Yan *et al.* 2019). This study thus showed that carbon fiber composites are not effective in absorbing low-frequency sound waves. In a previous study found in the literature, the sound absorption performance of laminated wood composite samples made from three different tree species (*Populus deltoides*, *Fagus orientalis* Lipsky. and *Betula* *pendula*) was investigated. The results indicated that the sound absorption performance of the composite materials was inadequate in the low-frequency range (Özyurt 2022).

A close examination of Fig. 3 reveals that the highest SAC values in the mid-frequency range (315 Hz to 1600 Hz) of the control, A, B, and C groups were determined as 0.19, 0.36, 0.39, and 0.45 at the 1600 Hz frequency, respectively. It was determined that the composite materials of the control group reflected or transmitted sound waves in the mid-frequency range. The evidence indicated that that plywood-carbon fiber composite materials absorb sound waves in the mid-frequency range with an efficiency of 36% to 45%. Additionally, it was determined that carbon fiber enhances the sound absorption performance of composite materials. The hybrid nature of the plywood-carbon fiber composite enhances its ability to dissipate acoustic energy through increased internal friction. Plywood, as a natural fiber-based material, possesses a porous structure that contributes to sound absorption, especially in the mid-frequency range where sound waves are more likely to interact with the internal voids and fibers, causing sound energy to be converted into heat through friction. When combined with carbon fiber, a material known for its high stiffness and tensile strength, the composite exhibits an improved structural damping effect. This is because carbon fiber can mitigate resonant vibrations and dampen mechanical waves more effectively than plywood alone, leading to a reduction in sound transmission and an increase in sound absorption. Moreover, the impedance mismatch between the layers of plywood and carbon fiber in the composite material enhances scattering of sound waves. The acoustic impedance difference creates conditions that lead to multiple reflections and scattering of sound waves within the material. The carbon fiber reinforcement also introduces additional internal interfaces that disrupt sound propagation, further contributing to energy dissipation and absorption. In contrast, the control group, with a sound absorption efficiency of only 19%, likely lacks these beneficial effects due to its homogeneous material structure, which is less capable of scattering sound waves or enhancing internal damping. The control material may exhibit a lower impedance contrast and fewer internal interfaces for sound wave disruption, resulting in poorer sound absorption performance in the mid-frequency range.

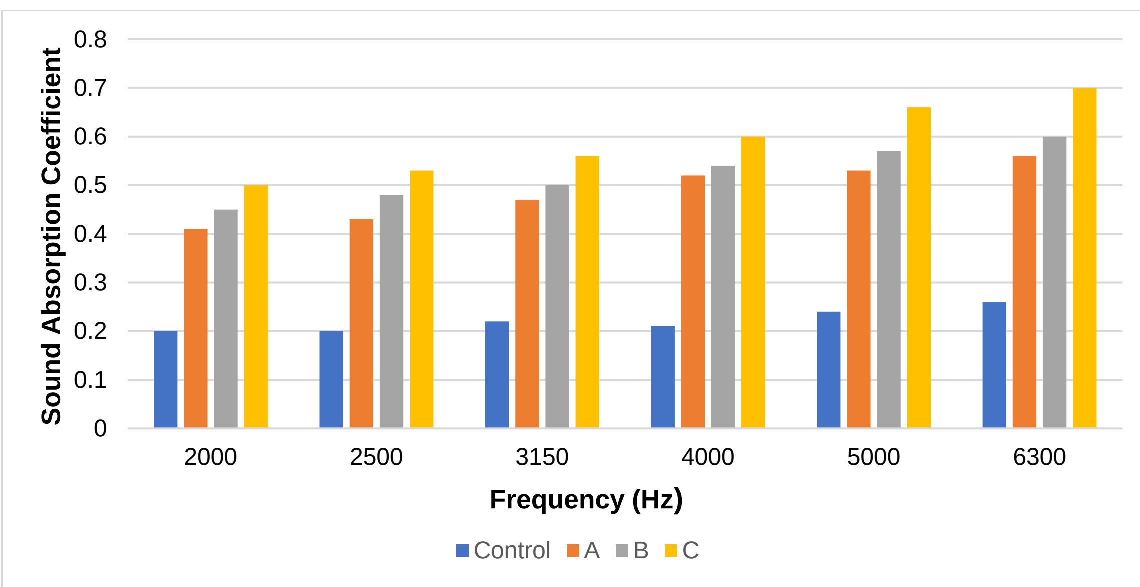

Fig. 4. High (treble) frequency SAC values of the control A, B, and C groups

In a study conducted on the sound absorption performance of carbon fiber material in the mid-frequency range (315 to 1600 Hz), it was determined that the carbon fiber material absorbs approximately 40% of the sound waves within this frequency band (Yan *et al.* 2019). In another study found in the literature, laminated wood composite panels were produced using poplar veneer, PVAc adhesive, natural rubber, elastomeric sponge, felt, and linoleum. The sound absorption performance of the produced composite materials was investigated. The results demonstrated that the reinforced laminated wood composite panels exhibited higher sound absorption performance compared to the control group (Özyurt and Özdemir 2022).

A detailed examination of Fig. 4 reveals that the control, A, B, and C groups exhibited more effective sound absorption capabilities in the high (treble) frequency range. The plywood and plywood-carbon fiber composite materials demonstrated the highest sound absorption performance at 6300 Hz within the 2000 Hz to 6300 Hz frequency range. The sound absorption (%) of the control, A, B, and C groups at 6300 Hz were measured as 26%, 56%, 60%, and 70%, respectively. It is evident that the plywood-carbon fiber composites exhibited high sound absorption performance. The study also found that carbon fiber significantly enhances the sound absorption performance of composite materials. This can be explained by the fact that the microstructure of carbon fiber composites was more effective at attenuating shorter wavelength (higher frequency) sound waves through increased internal friction and energy dissipation. Several studies in the literature have demonstrated that the sound absorption performance of Reinforced Laminated Wood (RLW) composite materials was significantly improved. These findings suggest that the incorporation of advanced materials and innovative design approaches in the lamination process enhances the acoustic properties of these (RLW) composites (Ghofrani *et al.* 2016; Özyurt and Özdemir 2022). The improved sound absorption is particularly notable in applications where sound quality and noise reduction are critical. This advancement underscores the potential of RLW composites as a viable material in environments demanding superior acoustic performance.

The findings of this research contribute to the existing body of knowledge in the field of wood material science and acoustics by introducing a novel composite material that combines plywood with carbon fiber, which exhibits improved acoustic performance compared to traditional plywood. This hybrid material, therefore, presents a new frontier in the design of sound-absorbing structures, bridging the gap between conventional wood-based materials and modern composite technologies.

CONCLUSIONS

1. It has been established that the incorporation of carbon fiber into laminated wood composites can markedly enhance their acoustic absorption capabilities.
2. The plywood-carbon fiber composites exhibited a tendency to reflect or transmit sound waves predominantly in the low (bass) frequency band, while demonstrating a high capacity for sound absorption at high (treble) frequencies.
3. The highest sound absorption performance of plywood and plywood-carbon fiber composite materials was determined at a frequency of 6300 Hz.
4. This study sets a foundation for future work, offering a basis for the development of advanced wood based composites with tailored acoustic characteristics for use

in architectural acoustics, automotive interiors, and other noise-sensitive environments. By building on these findings, future investigations could refine and expand the application scope of plywood-carbon fiber composites, leading to innovative solutions in sound absorption technology.

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