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Article

Study on the Sound Absorption Coefficient of Porous Coconut Wood Concrete Composite Materials in Concert Halls

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Abstract: This article investigates the sound absorption mechanisms of porous concrete and coconut wood fibers, exploring the effects of factors such as porosity, coarse aggregate, and thickness on the sound absorption coefficient of porous concrete. It also examines the impact of different treatment methods on the sound absorption coefficient of coconut wood fibers. Through acoustic research on both porous concrete and coconut wood fibers, the feasibility of porous coconut wood concrete soundproofing materials is proposed. Based on the conclusions of the above analysis, the advantages and disadvantages of using porous coconut wood concrete soundproofing materials in concert halls are explored from multiple perspectives and dimensions.

Keywords: sound absorption coefficient; coconut wood; concrete; pores; fibers; concert hall; sound waves; frequency

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1. Introduction

For concert halls, the sound-absorbing structures of walls, ceilings, floors, and other surfaces play a crucial role in controlling sound reflection and absorption. Effective sound-absorbing structures can reduce unnecessary reflections of sound waves during transmission, thereby enhancing the audio quality of performances in the concert hall. This not only meets the sound-absorption requirements of the concert hall's architectural structure but also improves the auditory experience for the audience. For residents living near concert halls, performances may disrupt their daily routines. However, the presence of sound-absorbing structures significantly reduces sound interference, thereby enhancing the quality of life for nearby residents. With the advancement of technology, an increasing number of sound-absorbing materials and structures have been discovered, such as wooden structures, fibers, and foam, which are widely used in sound-absorbing structures. However, most sound-absorbing materials and structures rely on excessive layering, resulting in high costs. Therefore, the development of cost-effective materials for sound-absorbing structures has become a growing area of focus. Along China's vast coastline, numerous coconut trees grow, and each year a large amount of coconut wood is discarded, causing significant pollution. In recent years, there has been extensive research on coconut wood fibers, but most of it has focused on their chemical and physical properties, with little attention given to acoustic studies related to sound insulation and sound absorption. Research has shown that coconut wood fibers exhibit excellent sound absorption properties [1]. Therefore, conducting research on the sound absorption properties of coconut wood fibers is particularly important.

2. The Effect of Porous Concrete on the Sound Absorption Coefficient of Coconut Wood Concrete Materials

This chapter explores the mechanism by which porous concrete materials influence the sound absorption coefficient, examining how the sound absorption coefficient changes under different void ratios, coarse aggregate gradations, and thicknesses of porous concrete. Through this research, the suitability of porous concrete for acoustic applications is proposed.

2.1. Mechanism of Porous Concrete Materials in Enhancing Sound Absorption Coefficients

For porous material structures, the sound absorption mechanism primarily consists of two aspects: viscous loss and thermal conduction loss. Viscous loss converts sound energy into thermal energy through friction between sound waves and the material, adhering to the principle of energy conservation, thereby achieving sound absorption. Thermal conduction loss, on the other hand, distributes the heat generated by viscous loss through thermal conduction to other areas, thereby enhancing the effect of viscous loss. Therefore, research on the sound absorption performance of porous materials primarily focuses on how to increase the rate and efficiency of sound-to-heat energy conversion in viscous loss. Li Guanda's team, based on this mechanism, conducted research on the influence of "forming pressure" and "bone glue ratio" on the sound absorption performance of porous concrete materials [2].

2.2. Determination of the Sound Absorption Coefficient of Porous Materials

The sound absorption performance of a material refers to the ratio of absorbed sound energy to incident sound energy during sound wave propagation, known as the sound absorption coefficient, denoted by α. If $\alpha = 1$, it indicates that all sound energy is absorbed. For sound-absorbing materials, most sound absorption coefficients α are less than 1 and approach 1. To calculate the sound absorption performance of a material, the standing wave tube method and reverberation chamber method are generally used for measurement. Coconut wood mixed soil materials are porous materials, and the standing wave tube method is typically used for porous materials, so the standing wave tube method was employed for measurement.

The standing wave tube method involves propagating a plane wave in a standing wave tube. The sound wave travels from the tube opening to the material surface, where it is reflected by the material to form a reflected wave. The incident wave and reflected wave interfere to form a standing wave within the tube, creating alternating regions of maximum and minimum sound pressure along the tube's length. According to the calculation formula, by determining the difference Lp between the maximum and minimum sound pressure values, the sound absorption coefficient of the material can be confirmed. In accordance with the relevant provisions of the national standard GBJ88-85 "Specifications for the Measurement of Sound Absorption Coefficient and Acoustic Impedance Using the Standing Wave Tube Method," the JTZB standing wave tube testing system is used to determine the sound absorption coefficient of the test specimen.

$\alpha_0 = \frac{4\times 10^{(L_P/20)}}{(1+10^{(L_P/20)})^2}$ (The formula is sourced from Reference [3])

By measuring the sound absorption coefficient with the standing wave tube method, we can experimentally determine how factors such as pore size and thickness influence the test specimen's sound absorption performance.

2.3. Influence of Pores on Sound Absorption Coefficient

The resistance to air flow through a material is called flow resistance. The smaller the pore size, the greater the flow resistance, and the higher the viscous loss of sound as it passes through the pores. Conversely, the larger the pore size, the smaller the flow resistance, and the lower the viscous loss of sound as it passes through the pores. Li Guanda's team investigated the effect of forming conditions on flow resistance in porous concrete, finding that at a forming pressure of 0.2 MPa, when the bone-to-cement ratio is between 0.7 and 0.8, increasing the bone-to-cement ratio promotes an increase in flow resistance. However, when the bone-to-cement ratio is between 0.8 and 1.0, increasing the bone-to-cement ratio leads to a decrease in flow resistance [3]. For porous materials, high flow resistance is beneficial for absorbing mid-to-high-frequency sound waves, but there is a risk that pores may be too small for sound waves to pass through. Low flow resistance is beneficial for absorbing low-frequency sound waves, but larger pores have weaker viscous effects. Therefore, when selecting pore sizes for materials, we must strictly choose appropriate pore sizes to enable the material to absorb low-, mid-, and high-frequency sounds simultaneously, thereby broadening the sound absorption frequency range of the material.

2.3.1. Influence of Porosity on Sound Absorption Coefficient

Concrete porosity refers to the percentage of pore volume relative to the total volume of concrete. The method for calculating porosity typically relies on the apparent density and actual density of each component. Porosity is closely related to strength in mechanical studies. In acoustics, the sound absorption coefficients of porous concrete samples with different porosities show little difference at low frequencies, but the differences are primarily evident at medium and high frequencies. However, overall, as porosity increases, the comprehensive average sound absorption coefficient α exhibits an increasing trend [3]. Zhou Shuai's team conducted research on the effect of artificial pores on the sound absorption coefficient (SAC) of porous concrete, finding that different combinations of artificial pores and pore depths significantly influence the sound absorption coefficient (SAC) of porous concrete [4].

2.3.2. Influence of Coarse Aggregate Gradation on the Sound Absorption Coefficient

Under the same void ratio, different coarse aggregate gradations result in different pore shapes, sizes, and numbers in concrete, thereby affecting the total specific surface area of the voids. Concrete with a high gradation has larger pore diameters, while concrete with a low gradation has smaller and more dispersed pore diameters. Under the same void ratio, the sound absorption coefficient decreases as the coarse aggregate gradation increases [3]. This is because porous concrete made from small aggregates has more sound absorption channels, and the increased complexity of these channels enhances sound absorption performance [5]. The A. Kapicová team compared ordinary aggregates, volcanic ash, Liapor, and recycled concrete aggregates, finding that volcanic ash had the highest sound absorption coefficient but poor mechanical properties [6]. Therefore, we need to consider the influence of coarse aggregate gradation on the sound absorption coefficient rather than the type of coarse aggregate.

2.4. Influence of Porous Concrete Thickness on the Sound Absorption Coefficient

Different thicknesses of porous concrete correspond to different frequencies of absorbed sound waves, as sound waves of different frequencies have different wavelengths. Due to varying thicknesses, porous concrete absorbs and reflects different sound waves, resulting in different sound absorption effects [5]. For sound waves of different frequencies, when the concrete thickness is between 24 mm and 60 mm, the higher the thickness of the porous concrete, the better its absorption effect on low-frequency sound waves. Conversely, the smaller the thickness, the better its absorption effect on high-frequency sound waves. Regarding the sound absorption coefficient, thinner porous concrete tends to have a lower sound absorption coefficient [3].

3. The Effect of Coconut Wood Fibers on the Sound Absorption Coefficient of Coconut Wood Concrete Materials

This chapter investigates how coconut wood fibers enhance the sound absorption coefficient of materials, explores the underlying mechanisms, and examines how these mechanisms change under various treatment methods. The study aims to understand how these changes influence the sound absorption coefficient of coconut wood fibers, ultimately seeking to develop efficient, low-cost, and high-performance coconut wood composite materials.

3.1. Mechanism of Coconut Wood Fibers Enhancing the Sound Absorption Coefficient of Materials

Coconut wood is chemically composed of cellulose, hemicellulose, and lignin. Coconut wood fibers contain numerous small tubular structures. When sound waves pass through these tubular structures, they induce viscous losses and thermal conduction losses within the tubes, thereby achieving sound absorption. Claudia Cilene Bittencourt da Silva's team studied the sound absorption capabilities of sisal, coconut shell, and sugarcane fibers at low frequencies using three different methods. They found that coconut shell fibers have sound absorption capabilities at low frequencies that are intermediate compared to sisal and sugarcane fibers, but still significant [7]. The wide tubular structure of coconut wood fibers provides excellent low-frequency sound absorption for composite materials, while the porous structure of concrete efficiently absorbs sound waves at medium and high frequencies.

3.2. The Effect of Coconut Wood Fiber Treatment on Sound Absorption Performance

Ordinary coconut wood fibers can be mixed into cement, combined with coarse aggregate, fine aggregate, water, and other elements, and undergo hydration to form concrete. Research indicates that treated coconut wood fibers undergo changes in their internal structure, such as gaps and composition, which enhance the material's sound absorption performance. To enable effective bonding of coconut wood with concrete for sound absorption, we applied alkaline, hammering, and thermal treatments to the coconut wood material. Shuaifeng Chen's team applied multiple treatment methods to coconut wood fibers, including alkali treatment, thermal treatment, and hammering treatment, to produce D-CW. They found that the treated coconut wood material has highly dense internal fibers and an anisotropic multi-layered stacked structure. These structures cause sound waves to have multiple reflection paths within the material, which is why it exhibits superior sound absorption performance [8]. Bamigboye Gideon Olukunle's team conducted acoustic studies on the composite material using coconut wood fibers at different ratios in concrete, finding that treated fibers exhibit significantly better sound absorption performance compared to untreated fibers [9].

3.2.1. Alkaline Treatment (NaOH)

Alkaline treatment decomposes the hemicellulose in coconut wood, removing impurities such as lignin, hemicellulose, pectin, and wax from the cellulose. The resulting fibers become rougher, enhancing their ability to absorb sound waves, thereby enabling coconut wood fibers to function more efficiently in coconut wood concrete composite materials. From a chemical perspective, alkaline treatment primarily converts the -OH groups in coconut wood fibers into alkoxy groups through reaction with NaOH, as shown in the chemical formula below [10].

$\mathrm{Coir - OH + NaOH \rightarrow Coir - O - Na + H_2O}$ (Chemical formula sourced from Reference [10])

3.2.2. Beating Treatment

Coconut wood fiber beating is a physical-mechanical modification method and a relatively niche fiber treatment approach. Compared to other methods, it has lower efficiency. The mechanism is similar: it separates microfibers from the original coconut wood fibers and creates smaller, more complex channels within the microfibers during the process, enhancing the material's ability to absorb sound wave energy.

3.2.3. Thermal Treatment

Thermal treatment enhances the strength of coconut wood fibers, decomposes organic compounds such as lignin and hemicellulose, improves fiber purity, alters the pore structure of coconut wood fibers, and enhances their sound absorption performance. Compared to alkaline treatment, thermal treatment is more environmentally friendly, cost-effective, and highly controllable, making it suitable for large-scale industrial applications. Jiang Lin's team baked coconut wood fibers at 180°C for 1 hour. They then recorded the sound propagation velocity, sound attenuation coefficient, sound reflection coefficient, and sound absorption coefficient of the fibers before and after thermal treatment. The measurement results clearly demonstrated that the acoustic properties of the coconut wood material were significantly improved after thermal treatment (Figure 1).

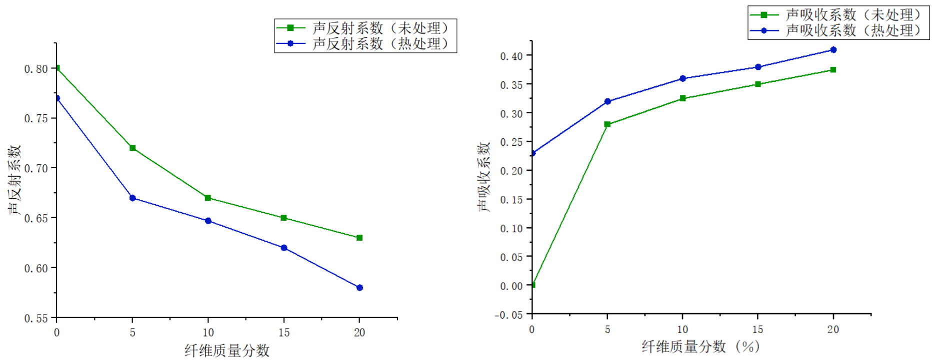

Figure 1. Comparison of sound reflection coefficients and sound absorption coefficients of coconut wood fibers before and after thermal treatment (data sourced from Reference [11]).

4. Research on the Application of Porous Coconut Wood Concrete Sound-Absorbing Mate-Rials in Concert Halls

Porous concrete structures and coconut wood fiber materials exhibit excellent acoustic performance, and their combination forms an efficient, low-carbon, and economical coconut wood concrete sound-insulating structure. This structure can meet architectural mechanical requirements while providing partial sound-absorbing functionality for concert halls, fulfilling sound-insulation standards and promoting the development of low-carbon buildings.

4.1. Advantages of Using Porous Coconut Wood Concrete Materials in Concert Halls

Coconut wood concrete composite materials formed by adding coconut wood fibers to cement exhibit significantly enhanced durability compared to ordinary concrete materials, as coconut wood fibers have a certain inhibitory effect on the formation of concrete cracks, which also results in more pronounced mechanical properties of the composite structure [12].

4.1.1. Excellent Sound Absorption Performance

Porous concrete, due to the numerous pores within it, can absorb and dissipate a large amount of sound energy. Coconut wood fibers also contain numerous microscopic pores. The combination of the two forms porous coconut wood concrete material, which can absorb sound waves from low to high frequencies, achieving comprehensive, multi-frequency sound absorption performance and meeting the requirements of music acoustic design. Reverberation time is a critical factor directly influencing audience perception and is also an important indicator for evaluating the acoustic quality of a concert hall. According to the Sabine formula, reverberation time is closely correlated with the total sound absorption capacity of the interior space [13].

4.1.2. Excellent Strength

The Trokon Cooper Herring team compared concrete beams with coconut wood reinforcement and those without, finding that the reinforced concrete beams could enhance the ductility of the components without reducing their ultimate load-bearing capacity, significantly improving the building's seismic performance [14]. The use of porous coconut wood concrete composite structures in concert halls can greatly increase the durability of the building. Moreover, this composite structure enhances the ductility of beam structures and improves the ultimate load-bearing capacity of column and slab components, which contributes to enhancing the seismic resistance of the concert hall building.

4.1.3. Aligning with the Trend toward Low-Carbon Buildings

According to data from the United Nations Environment Programme, the global construction industry accounts for approximately 40% of energy consumption and 30% of greenhouse gas emissions. The trend toward low-carbon buildings is urgent in the construction industry. The Naraindas Bheel team, addressing the issue of low-carbon buildings, found that using coconut shell ash as an auxiliary gel material in concrete can reduce carbon emissions by approximately 11.78% [15]. The use of porous coconut wood concrete composite materials in concert halls aligns with the global trend toward low-carbon buildings, effectively reducing carbon emissions and benefiting the environment. Additionally, there is a significant amount of waste coconut wood, which, when discarded improperly, causes environmental pollution. The application of porous coconut wood concrete composite materials can, to some extent, alleviate the issue of waste coconut wood disposal [16]. The development of porous coconut wood concrete composite materials aligns with the principles of low-carbon construction [17].

4.2. Limitations and Prospects of Research on Porous Coconut Wood Concrete Structures in Concert Halls

This paper's research on coconut wood structures is limited to the combination of coconut wood and concrete materials. Based on the properties of these two materials, it explores the acoustic effects of coconut wood concrete composite materials [18]. However, due to experimental limitations, there is no clear ratio of coconut wood to concrete that ensures optimal sound absorption coefficients. Regarding the acoustic effects in concert halls, this paper only focuses on the sound absorption coefficients of concrete and coconut fiber composite materials. However, there are many other factors that influence acoustic effects in concert halls, such as wooden panels, foam boards, and other plant fiber materials, which also have a certain degree of influence on acoustic materials and can enhance their sound absorption functions [19].

5. Conclusion

Music hall buildings have high requirements for sound absorption coefficients. Research on the sound absorption coefficients of porous coconut wood concrete composite materials can, to a certain extent, meet the requirements of both building structure and sound absorption coefficients, achieving a structure that satisfies both aspects. This holds significant importance for music hall buildings. This article delves into the underlying mechanisms to elucidate the importance of porous coconut wood concrete composite materials in enhancing the sound absorption coefficient of concert halls, while also highlighting their advantages and disadvantages. We hope this material can be effectively applied in practical scenarios, providing valuable references and assistance for future concert hall architectural designs.

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