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COMPREHENSIVE ANALYSIS OF SOUND ABSORPTION COEFFICIENT (SAC): MATERIALS, METHODS, AND MODELING FOR ADVANCED ACOUSTIC PERFORMANCE

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Abstract This paper compiles the recent research findings on the Sound Absorption Coefficient (SAC), which is one of the most important factors in material performance in terms of acoustics. It reviews the effects of material properties, shape features, and optimization methods on SAC. SAC values of natural fibers, nonwoven fabrics, and composites are high, with the SAC performance influenced by thickness, density, and porosity. SAC prediction and optimization are improved by state-of-the-art techniques such as Response Surface Methodology and Artificial Neural Networks. Importantly, recycled materials have competitive SAC values, which is in sync with sustainable trends. The work also identifies various factors that influence SAC and opens possibilities for the creation of efficient and environmentally friendly acoustic systems. Further improvements of the existing predictive models are expected, as well as the analysis of the material performance in real-use conditions.

Keywords: Sound Absorption Coefficient (SAC); acoustic materials; natural fibers; nonwoven fabrics; composites; Response Surface Methodology; Artificial Neural Networks; sustainable acoustics; porous structures.

1. INTRODUCTION

The Sound Absorption Coefficient (SAC) is one of the most important acoustic properties of materials that can be used for the assessment of their acoustic characteristics. It defines the ability of a material to absorb sound energy, which is very important in noise control and acoustic engineering in different settings. This synthesis looks at the current research done on SAC, in particular, the materials and techniques that have been employed to improve the sound absorption properties.

2. MATERIAL COMPOSITION AND SAC ENHANCEMENT

Kenaf and Yucca Gloriosa are among the natural fibers that have demonstrated promising SAC values, while performance is improving with the increase in thickness and bulk density [1, 2]. Kenaf (Hibiscus cannabinus) and Yucca Gloriosa have good sound absorption coefficients (SAC) that suggest these materials' use in acoustic applications. Other research also shows that the sound absorption properties of these materials are dependent on thickness and bulk density. For instance, Taban et al. (2020) showed that Kenaf fibers, when optimized in terms of thickness and density, can significantly attenuate sound transmission and, therefore, could be used in buildings where sound insulation is paramount [1]. In the same way, Soltani et al. (2020) also discovered that the Yucca Gloriosa fibers also exhibit improved sound absorption properties, especially at the higher frequency range, which is crucial in reducing noise in various settings [2].

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The capability of these natural fibers for sound absorption can be ascribed to the porosity of the fibers and other characteristics of the fibers that facilitate sound energy to be dissipated. As the thickness of the insulation material increases, the SAC is also seen to increase, which is an implication that thicker layers are more effective at sound absorption. This relationship, therefore, underscores the need to choose the right materials and arrange them in the right manner when designing acoustic solutions in construction and interior design. Moreover, the bulk density of these fibers is important because denser materials are known to provide better sound absorption because they can capture sound waves better. Therefore, the use of Kenaf and Yucca Gloriosa fibers in soundproofing offers an environmentally friendly solution while at the same time improving the acoustic quality of built structures.

SAC of nonwoven fabrics depends on fiber diameter, thickness and porosity, the best combination of which provides better sound absorption [3,4]. Studies have also indicated that these parameters are very critical in the determination of the sound absorption properties of nonwoven materials. For example, Soltani and Norouzi (2020) [3] performed a detailed examination that explained that the differences in fiber diameter can impact the SAC; finer fibers are more effective in sound absorption since they have a larger surface area and better interaction with sound waves. Thicker nonwoven fabrics also have higher SAC values because the extra material offers more routes for sound energy to be transmitted hence reducing the transmission.

In addition, there is another significant factor that affects the SAC of nonwoven fabrics, which is porosity. Higher porosity will result in increased airflow through the material, which may increase the rate of sound wave attenuation through viscous and thermal means. Besides, Palak and Kayaoğlu (2020) [4] investigated the effects of bonding methods and fiber cross-sections on the sound absorption performance of PET fiber-based nonwovens, which established that the performance can be enhanced with the proper selection of the configuration.

From consideration of these factors, it can be deduced that when the fiber diameter, thickness of nonwoven fabric, and porosity are properly chosen, the sound absorption properties will be improved. This knowledge is crucial in the design of proper acoustic systems in different areas of application, including building structures, and automobile industries where the use of sound absorption materials in interior trims is of significant importance in the reduction of noise. Hence, the management of these properties can bring about enhanced sound absorption of nonwoven fabrics, which can be useful in the search for better acoustic performance.

Research has shown that composite materials, which combine two or more components, often exhibit enhanced sound absorption performance compared to single-material samples. This improvement in SAC can be attributed to the synergistic effects of the different components within the composite structure.

Samaei et al. (2021) [5] studied the sound absorption characteristics of a new natural fibro-granular composite containing kenaf fibers and rice husk particles. They also showed that the composite material with the best thickness, density, binder content, and fiber-to-granule ratio offered better sound absorption in all the frequency ranges than the samples made of kenaf fibers or rice husk granules only. This implies that there is a potential for incorporating various materials in a composite so as to enhance the sound absorbing system.

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The following are the factors that can be attributed to the enhanced SAC of composite materials. First of all, since the given materials possess different physical and acoustic parameters, the sound waves will have to traverse through a more complicated and winding path, which in turn will cause the energy loss through viscosity and thermal effects. Secondly, the integration of different components in a composite can lead to new sound absorption mechanisms including friction at the interfaces and damping.

Furthermore, the structure of composite, including arrangement and distribution of the components, may enhance sound absorption performance of the composite even further. Through proper design of the composite material and proper selection of the components, the researchers and engineers can formulate the SAC to fit certain acoustic needs that are needed for different fields such as construction, automobiles, and noise control.

3. GEOMETRICAL AND PHYSICAL PROPERTIES INFLUENCING SAC

Previous works reveal that the size and shape of sound-absorbing samples affect their SAC because of edge effects that change the way sound waves are absorbed by the material. Zhao et al. (2023) [6] also note that changes in dimension of the sample especially in rectangular shape can cause different acoustic performance since sound waves can take different paths through the edges changing its overall absorption.

Bigger samples normally have more stable SAC values as they reduce the possibility of edge effects that may occur in relatively small samples. This happens because in small samples a larger part of their surface area lies at the edges where sound waves can bounce back instead of being absorbed. Therefore, the empirical models derived in the previously mentioned study can be used to predict SAC with geometrical parameters and can be used for the improvement in the design of sound absorbing materials for practical use.

In addition, the rate of the incident sound has been found to be an important factor that determines the size and shape of the SAC. Different frequencies of electromagnetic radiation interact with the material in a certain manner, and the shape of the sample can either increase or decrease the absorption of a certain range of frequencies. Hence, the information on the relationship between the sample dimensions and SAC is vital in the design of acoustic modifications in different spaces like concert halls, recording studios and offices.

Certain studies have also shown that the material's porosity, which is the ratio of the volume of pores to the total volume of the material, like in the case of honeycomb structures and asphalt concrete can increase the SAC. This improvement in sound absorption performance can therefore be considered as a consequence of the existence of specific microstructure of these materials.

In the case of porous asphalt concrete, increased void ratio enhances air flow through the material, and thus energy losses by viscosity and thermal effects. As observed by Xie et al. (2022) [7], the air voids in the asphalt concrete affected the SAC of the material. An increase in the void produces higher sound absorption capacity. This implies that the void structure should be well optimized to enhance the acoustic properties of asphalt materials.

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Similarly, the structures with honeycomb patterns which contain a system of voids also display enhanced SAC. The structure of honeycomb materials makes it difficult for the sound wave to pass through and this results in many reflections of the sound energy with the material. Xie et al. (2020) [8] pointed out that filled honeycomb composites can provide sound attenuation over a broad frequency range with the help of properly designed voids.

4. OPTIMIZATION TECHNIQUES FOR SAC IMPROVEMENT

RSM (Response Surface Methodology) and CCD (Central Composite Design) are very effective statistical methods of studying the effect of the parameters that affect the sound absorption coefficient of composite materials such as thickness, density and binder content. These methodologies allow the researchers to examine the interconnection of various factors and their impact on SAC which results in improved and optimized material design.

With the help of RSM, it is possible to build a mathematical model that would show how SAC depends on the changes of the given factors. This approach enables the determination of the most suitable thickness, density and binder content that results in the best sound absorption at different frequencies.

According to Samaei et al. (2021) [5], the use of CCD helped in the analysis of the effects of the various factors on SAC. For instance, changing the thickness of the composite material may greatly change its acoustic performance because thicker materials offer more channels for sound waves to travel through. Likewise, the density variations are also known to alter the material's porosity and therefore its capacity to capture sound. The binder content can also be considered as an important factor since it can affect the mechanical properties of the composite.

Applying RSM and CCD, the researchers are able to control the SAC of the composite materials and make them meet certain acoustic requirements. This optimization process not only improves the sound absorption properties of the materials, but also supports the advancement of effective and environmentally friendly noise control strategies.

ANN (Artificial Neural Networks) and regression models have also been applied for predicting the sound absorption coefficient (SAC) where the models have shown their potential in identifying the intricate interconnections between different factors. Ramamoorthy and Rengasamy (2018) [9] worked on the investigation of the influence of fiber deniers and shapes on the acoustic properties of needle punched nonwovens with an air gap. They assessed the ability of ANN and conventional regression analysis in predicting SAC. The results indicated that although both methods can give quite helpful predictions, ANN might be more precise in some cases. This is because ANN is capable of handling non-linear relationships and multiple interactions between the different variables in comparison to the linear regression models.

The strength of the ANN is that it is capable of making predictions from given data and additionally refining its predictions as it receives more data. This is especially so in the context of SAC given that there are so many factors that come into play including the density of the material, the thickness, the porosity of the material and the characteristics of the fibers used in the material. Therefore, through training of ANN on experimental data, researchers can come up with accurate models that not only forecast SAC but also determine the right parameters of sound absorption materials.

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Moreover, since ANN has the potential to analyze huge amount of data and identify trends that are not easily discernible, it is a useful tool for researchers and engineers who want to create and enhance acoustic materials. Given the increasing need for efficient noise control products, the application of ANN in designing materials with particular acoustic properties will be vital.

The application of Artificial Neural Networks and regression models in determining sound absorption coefficients shows that there is a need to incorporate sophisticated techniques in the analysis of acoustics. In particular, ANN, provides higher precision in many cases, which enables the improvement of material characteristics and design parameters to increase sound absorption in numerous applications.

5. SAC PERFORMANCE OF RECYCLED AND SUSTAINABLE ACOUSTIC MATERIALS

Recycled materials, especially, resin-bonded denim composites, have the possibility of attaining competitive sound absorption coefficient (SAC) values and thus can be considered as potential substitutes for conventional synthetic sound absorbers. Hassani et al. (2021) [10] have found that the porosity of the recycled denim fabric bonded with resin is the main factor that enhances its sound absorption properties. The characteristics of the recycled denim fibers and the resin system used in the present work result in a material that can reduce sound energy through viscous and thermal losses. Consequently, the SAC of these composites can be on par with synthetic materials that are commonly made from petrochemical feedstocks.

Several factors may be attributed to the competitive SAC values realized by the recycled denim composites. First, the denim fabric has a fibrous structure which creates a greater area for sound wave contact and therefore makes the material effective in sound absorption at different frequencies. Also, the composite has pores through which air can be trapped thus enhancing the sound absorption properties of the composite. This property is especially advantageous for the low frequency sound absorption in which artificial materials often fail.

Furthermore, the factor of sustainability that comes with using recycled material to make sound absorption adds another layer of value to the application. These composites made from denim waste can effectively reduce the environmental pollution and at the same time provide a cheap solution for noise control. With the growing concern of industries to find sustainable solutions for synthetic materials, the creation of efficient sound-absorbing materials from recycled sources is more and more relevant.

The SAC values obtained for the resin-bonded recycled denim show that the recycled materials can offer comparable performances to non-recycled ones, which underlines the potential of the latter as efficient sound absorbers. This development also adds to the need for green building and also shows the need to research on new materials that can provide the required acoustic performance while at the same time having a positive impact on the environment.

6. CONCLUSION

The Sound Absorption Coefficient (SAC) is identified as a vital factor in the assessment and improvement of acoustic materials, based on the literature analyzed in this paper. These findings highlight the fact that SAC is influenced by a number of factors such as composition, geometry and

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physical structure of the material which makes the phenomenon of sound absorption a rather complex one. Nonwoven fabrics and natural fibers as well as composite materials have relatively high SAC values with characteristics such as thickness, density, and porosity affecting their performance. These findings show that there is an opportunity to create high-performance, sustainable acoustic systems.

Application of advanced optimization techniques like Response Surface Methodology and Artificial Neural Networks has greatly improved the prospects of accurately modeling and improving the SAC for a wide range of material configurations. These methodologies not only enhance the reliability of SAC predictions but also enhance the development of specialized acoustic materials for use in specific contexts. In addition, the competitive SAC values obtained for recycled materials, for instance, resin-bonded denim composites suggest that there is potential for sustainable acoustic engineering without sacrificing performance.

This paper's synthesis of the literature demonstrates that SAC optimization is a complex and multi-disciplinary field that includes material science, statistical analysis, and sustainable decision making. In the further development of the field, these various aspects will need to be incorporated in order to produce the next generation of acoustic materials. Future works should aim at enhancing the predictive models, discovering new sustainable materials, and evaluating the durability of the materials in practical applications that are SAC-optimized. This integrated approach to SAC research and application is highly promising for the further development of acoustic engineering in different spheres of human activity, including architecture and transport, as well as for solving urgent ecological problems.

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