Applied Acoustics 126 (2017) 58–67

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Acoustic absorption of fibro-granular composite with cylindrical grains

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A R T I C L E I N F O

Article history:
Received 25 December 2016
Received in revised form 10 May 2017
Accepted 11 May 2017

Keywords:
Natural fiber
Natural grain
Acoustic absorption
Fibro-granular composite
Cylindrical grain

A B S T R A C T

This paper reports the influence of cylindrical granular materials on the acoustic absorption performance of a natural fiber composite. The acoustic absorption behavior of an innovative fibro-granular composite composed of natural fibers combined with granular materials was investigated. The fibrous part of this new composite is fabricated using coconut coir fiber and the granular part by cylindrical rice husk grain. This study was motivated by a desire to improve the acoustical performance of materials made from natural (coir) fibers. The amount of binder additive added during composite preparation was considered by reconstructing the equation using fiber diameter as a new parameter. The acoustic properties of the novel composite were investigated based on the well-known Johnson-Champoux-Allard model by varying different physical parameters. The experimental analysis was performed in impedance tube to validate the analytical outcome. The developed analytical model employing Johnson-Champoux-Allard model was found to give predictions in good agreement with absorption coefficient data for the composite material samples with four different thicknesses. The effect of varying the different factors, such as sample thickness, fiber–grain size and fiber-grain ratio, on the acoustic absorption performance and the effect of the binder additive were also investigated. Results confirmed the potential of the new material as a promising acoustic absorber in the low-frequency region (less than 1 kHz).

1. Introduction

Traditional acoustic materials, which have provided acceptable absorption rates for nearly all frequency bands, cannot satisfy all issues in environmental pollution and waste management. Acoustic materials from natural waste materials have received attention to address the dominant use of expensive and non-biodegradable materials. The natural substance has a high potential for sound absorption because of its light weight, natural abundance, cost efficiency, biodegradability, and eco-friendliness. Thus, natural and recycled acoustic materials are valid alternatives to conventional synthetic materials [1].

Recycled and natural granular materials are highly sustainable, non-combustible, and moisture-resistant acoustic absorption materials. Most granular absorbents contain air-filled pores, where sound absorption takes place due to viscous boundary layer effect. The viscous loss occurs in the boundary layer of air adjacent to pore walls by means of friction between the air molecules and the pore walls. This phenomenon causes the sound energy to be dissipated as heat [2].

Coir fiber is an important natural waste material because of its outstanding potential to replace conventional fibers, such as glass fibers or rock wool, for noise absorption. The fibrous structure of an individual fiber cell is hollow, and this hollow cavity decreases the bulk density and makes the coir fiber light and delicate to serve as a reliable acoustic and thermal insulator [3].

Rice husk is a great resource as a natural waste material, which comes from a commonly cultivated crop paddy and is abundant worldwide. It is highly resistant to moisture, noncombustible, and presents antifungal quality. Rice husk waste, together with polyurethane binder, has been investigated as a potential low-frequency acoustic absorber [4].

Several researchers have successfully developed sound absorbers by combining fiber and plastic or rubber-based granular materials [5,6]. Berardi and Innace [7] reported the effectiveness of a composite consisting of cork and canes (bark and wood) as potential acoustic absorbers in terms of the Delany-Bazley model. Mean-

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http://dx.doi.org/10.1016/j.apacoust.2017.05.012
0003-682X/

while, Mahzan et al. [8] investigated the effectiveness of the coir fiber-recycled rubber composite as a potential acoustic absorber. In their study, the composite with optimum composition of 40% coir fiber and 60% recycled rubber granulates was identified as a promising sound absorption material.

Koizumi et al. [9] reported that high tortuosity, high surface area, high flow resistivity, and low porosity at optimal values are the key factors for effective sound absorption performance of any material.

Despite their great availability and biodegradability, fresh natural fibers cannot be extensively applied industrially because of their moisture content, thick diameter, and low antifungal quality. In addition, industrially treated natural fiber with lower moisture content compared with fresh natural fiber lead to lower acoustic absorption performance [10]. The current study reports, that this acoustic attribute can be improved by incorporating granular materials in fibers to modify moisture content.

The authors have previously highlighted the limitations of natural fibers in achieving the desired acoustic absorption performance at the desired frequency range, which is below 1 kHz [11]. Hence, the current study named and investigated the acoustic performance of a new composite which is fibro-granular composite. Usually, it consists of natural, rubber, or plastic granulates and natural or synthetic fibrous materials.

The purpose of this study is to investigate the acoustic absorption characteristics of a natural fibro-granular composite to overcome the drawbacks of a single natural fiber composite. The acoustic absorption performance of 30 mm thick composite sample was plotted through analytical and experimental methods. Subsequently, the possible effects of sample thickness, fiber-grain size, binder additive and fiber–grain ratio were analytically investigated for the enhancement of acoustic absorption of this newly developed composite at the low-frequency region ($f < 1000$ Hz).

Coir fiber and rice husk grain are the acoustic materials which were used in this study. The well-known rigid frame Johnson-Champoux-Allard model was employed for analytical analysis. Impedance tube measurement was performed for experimental analysis and the results were compared with analytical results to validate the findings. This innovative material can be applied in the automotive industry, buildings, and indoor and outdoor sound control.

2. Methodology

2.1. Theoretical measurement: Johnson-Champoux-Allard model

Various techniques are used to predict the acoustic absorption mechanism in porous media. Almost all these techniques describe the acoustic parameters, such as characteristic impedance and propagation constants of porous materials. The Johnson-Champoux-Allard model is a rigid-frame model, in which the solid phase of the frame remains motionless. The model was developed by Allard and Champoux [12], according to the previous work by Johnson et al. [13]. Five non-acoustic parameters, namely, flow resistivity, porosity, tortuosity, viscous characteristic length, and thermal characteristic length, are considered in this model to predict the acoustical parameters. Viscous characteristic length and thermal characteristic length are the shape factors related to viscous and thermal loss, respectively.

Considering the effects of viscosity, Johnson et al. [14] defined the frame geometry-dependent parameter of viscous characteristic length (Λ) as follows:

$$\Lambda = 2\frac{\int v_{fluid}^2 dA}{\int v_{fluid}^2 dV}. \tag{1}$$

where the numerator denotes the velocity of a fluid over the pore surface area A, and the denominator denotes the velocity inside the pore volume V.

Moreover, Johnson et al. [14] described the relation between the viscous characteristic length and flow resistivity (σ) as follows:

$$\Lambda = \frac{1}{c}\left(\sqrt{\frac{8\eta\alpha_\infty}{\sigma\varphi}}\right) \tag{2}$$

where α_∞ is the tortuosity, φ is the porosity, and c is a constant, which is close to one.

Johnson et al. [13] proposed the following expression of the effective density $\rho(\omega)$ of rigid-framed porous materials:

$$\rho(\omega) = \alpha_\infty\rho_o\left[1 + \frac{\sigma\varphi}{j\omega\rho_o\alpha_\infty}\sqrt{1 + \frac{4\alpha_\infty^2\eta\rho_o\omega}{\sigma^2\Lambda^2\omega^2}}\right]. \tag{3}$$

where Λ is the viscous characteristic length.

As long as the material is air-filled, then thermal exchange between pore-borne sound wave compressions and rarefactions and the pore walls is significant as well. This is why, the Johnson-Champoux-Allard model includes a thermal characteristic length and thermal exchange is responsible for the thermal losses. Hence, according to Allard and Champoux [12], the thermal characteristic length Λ', which characterizes the high-frequency behavior of the bulk modulus $K(\omega)$, is given as follows:

$$\Lambda' = 2\frac{\int^d A}{\int^d V} = 2\frac{A}{V} \tag{4}$$

For fibrous materials with porosity close to one, Λ and Λ' can be stated as Eqs. (5) and (6), respectively [15], as follows:

$$\Lambda = 1/2\pi rl \tag{5}$$

$$\Lambda' = 1/\pi rl = 2\Lambda \tag{6}$$

The total length of fiber l per unit volume can be expressed as follows:

$$l = \frac{1}{\pi r^2} \tag{7}$$

where r is the cross-sectional radius of the fiber.

Allard and Champoux [12,15], proposed the following expression of the bulk modulus $K(\omega)$ of rigid-framed porous materials:

$$K(\omega) = \frac{\gamma P_o}{\gamma - (\gamma - 1)\left[1 - j\frac{8\eta}{\Lambda'^2 N_p \rho_o \omega}\sqrt{1 + j\frac{\Lambda'^2 N_p \rho_o \omega}{16k}}\right]^{-1}} \tag{8}$$

The characteristic impedance $Z_c(\omega)$, complex wave number $k_c(\omega)$, and surface acoustic impedance Z can be estimated as follows [15,16]:

$$Z_c(\omega) = \frac{1}{\phi}\sqrt{\rho(\omega)\cdot K(\omega)} \tag{9}$$

$$k_c(\omega) = \omega\sqrt{\rho(\omega)/K(\omega)} \tag{10}$$

$$Z = Z_c(\omega)\cdot \coth(k_c(\omega)) \tag{11}$$

With the surface acoustic impedance Z, the absorption coefficient α, at a normal incidence of the porous layer while backed with a rigid wall can be calculated as follows:

$$\alpha = 1 - \left|\frac{Z - Z_0}{Z + Z_0}\right|^2 \tag{12}$$

where $Z_0 = \rho_0 c_0$ is the impedance of air.