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Acoustical properties of novel sound absorbers made from recycled granulates

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ABSTRACT

This study investigates the acoustic performance of materials made using various amounts of bio-binder (cis-1,4-polyisoprene). The filler used in making these materials was from recycled tyres which consist of nylon 6,6 fibres bonded to rubber grains known as tyre shred residue (TSR). The materials have shown high acoustical performance especially at low binder levels, due mainly to the open porosity of the tested samples.

The paper begins with a discussion of materials made using recycled granulates. The macroscopic properties (e.g. flow resistivity, porosity, tortuosity, etc.) that control the acoustical behaviour of these materials are then defined as are methods for their measurements. The acoustical characterisation of porous media is considered next, followed by discussion of the acoustic performance of the materials. The characteristics of these novel materials are illustrated through experimental and theoretical models involving sound absorption and transmission.

1. Introduction

Polymers, plastics and elastomers, useful as they are in the modern world, have nevertheless created an abundance of waste residues that are not normally recyclable and continue being disposed to landfills, stockpiles or illegal dumps. These are residues or scrap of materials derived from tyres, vehicles furnishing, plastic carpet tiles and the like which consist of plastic fibres trapping rubber particulates (see Fig. 1). These residues are difficult to separate and then recycle, for example a single tyre granulating company can produce up to 30 tonnes of tyre shred residue per day which ends up in the landfill. This research deals with such residues and seeks to transform them into value added acoustic materials using a bio-binder (cis-1,4-polyisoprene). The novel acoustic materials can be tailored for noise absorption or transmission loss around buildings, industrial and domestic appliances.

The authors are not aware of materials that have been made previously using bio-binders with tyre shred residue as the filler; the materials were produced in the acoustics laboratory at the University of Bradford. However, there has been a lot of work on the acoustical properties of sustainable materials which are made of organic waste. Works by Horoshenkov et al. [1] and Asdrubali et al. [2] have revealed the potential of sustainable materials made from recycled and natural materials. Subsequent works, some of them carried out by the present authors, have shown that natural materials could be designed to select the frequency range of maximum efficiency [3]. The aforementioned works consider that the high porosity in TSR is inherited from the fibrous component in the filler, the composition of TSR used to make the materials were 80% rubber to 20% nylon 6,6 fibres by weight. It should be underlined that some porous material manufacturing processes may give rise naturally to the existence to high porosity.

To better understand the acoustic behaviour of these materials it was necessary to characterise the materials and investigate parameters which influence the absorption mechanisms taking place within them. Furthermore, the knowledge of the internal structure of the materials would be useful to achieve a better understanding of formulating low cost materials for acoustic applications to achieve optimum sound absorption. Previous studies with a similar sustainability purpose [4] used synthetic binders to bond the particulates together to create porosity stratifications within the materials, here we use a low cost bio-binder to structure them in either partially closed or open pores.

In this paper, porous materials made using bio-binder will be characterised according to the macroscopic physical properties that determine their acoustical performance, the techniques used for measuring these quantities will be discussed. Finally, a five parameter ***Johnson Champoux Allard model will be used to predict the wave propagation in these materials.

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Nomenclature

$\rho_e(\omega)$	complex dynamic density
$K_e(\omega)$	dynamic compressibility
$K_e(\omega)$	flow resistivity
ϕ	porosity
α_∞	tortuosity
Λ	viscous characteristic length
Λ'	thermal characteristic length
ρ_0	density
η	viscosity of air
N_p	Prandtl number
κ	specific heat ratio
P_0	static pressure
Z_c	characteristic impedance
k_c	complex wave number
V	flow velocity
ΔP	pressure drop
Δx	thickness
ρ_f	density of the material frame
ρ_m	density of the material
Δt	time delay
a_{Si}	1/3 octave of sound absorption
L_i	sound pressure level

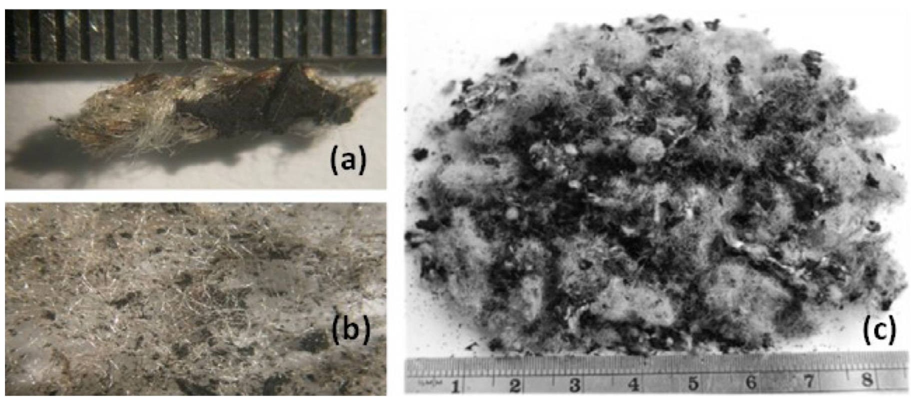

Fig. 1. (a) Microscopic image of rubber crumb attached to fibres, (b) Nylon 6,6 fibres, (c) granulated raw tyre shred residue.

2. Modelling sound propagation within rigid frame porous media

In porous media the absorption mechanisms of sound result from thermal and viscous effects occurring in the pores, in most cases the porous material is assumed to behave like a visco-thermal equivalent fluid i.e. porous material is supposed to have a rigid frame, much more rigid and heavier than air. In this situation the acoustic waves only propagate through the air within the pores of the acoustic material. In particular, viscous and inertial effects are taken into account by introducing a complex dynamic density, $\rho_e(\omega)$[kg/m^3], whereas thermal exchanges are described by a complex dynamic compressibility $K_e(\omega)$[Pa].

For the calculation of the effective properties Johnson et al. [6] proposed a semi-phenomenological model to describe the complex density of an acoustical porous material with a motionless skeleton having arbitrary pore shapes, the expressions to calculate the equivalent fluid in one pore is presented in Eqs. (1) and (2). In the calculation of the dynamic density $\rho_e(\omega)$ four parameters are involved; the static air flow resistivity (σ), the open porosity (ϕ), the high frequency limit of the tortuosity (α_∞) and the viscous characteristic length (Λ). Champoux and Allard [5] introduced an expression (Eq. (2)) for the dynamic bulk modulus for the same kind of porous material based on work carried out by Johnson, Koplik and Dashen [6].

$$\rho_e = \alpha_\infty \rho_0 + \frac{\sigma\phi}{i\omega}\sqrt{1 + \frac{4i\alpha_\infty^2 \eta \rho_0 \omega}{\sigma^2 \Lambda^2 \phi^2}} \tag{1}$$

and

$$K_e = \frac{k \cdot P_0}{k - (k-1)\left[1 + \frac{8\eta}{i\rho_0\omega N_p \Lambda^{prime2}}\sqrt{1 + \frac{i\rho_0\omega N_p \Lambda'^2}{16\eta}}\right]^{-1}} \tag{2}$$

where ρ_0 and η are the density and the viscosity of air, N_p is the Prandtl number, κ is the specific heat ratio and P_0 is the static pressure. The complex dynamic density and dynamic compressibility depend on five macroscopic parameters presented in Eqs. (1) and (2), the airflow resistivity (σ), the open porosity (ϕ), the tortuosity (α_∞), and the viscous (Λ) and thermal (Λ') characteristic lengths.

The characteristic lengths Λ and Λ' represent the average macroscopic dimensions of the pores with respect to the viscous and thermal losses, respectively. The thermal characteristic length Λ' reflects the pores of larger size, where thermal transferring surface is significant. By contrast, the viscous characteristic length Λ reflects the importance of airflow in the pores and thus represents the smaller pores due to the high air particle velocity at these locations. In other words, Λ' stands for the average radius of the largest pores, while Λ represents the average radius of the smallest pores. The ratio Λ'/Λ is always higher or equal to 1. Based on the work of Johnson et al. [6], it can be shown that Λ' is generally larger than Λ if the flow is considered laminar. Further information about the above mentioned quantities can be found in [5,6].

The characteristic impedance (Z_c) and complex wave number (k_c) can be deduced from these complex parameters, with:

$$Z_c = \sqrt{\rho_e . K_e} \quad [\mathrm{Ns/m^3}] \tag{3}$$

and

$$k_c = \omega\sqrt{\rho_e / K_e} \quad [\mathrm{m^{-1}}] \tag{4}$$