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Sound absorption enhancement using solid–solid interfaces in a non-porous cement-based structural material

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ABSTRACT

This work shows that solid–solid interfaces in a non-porous stiff material can enhance the sound absorption and provides an analytical model for describing the effects of constituents and interfaces on the sound absorption. The sound absorption coefficient α, the propagation constant Γ and the reflectivity R were determined for cement-based materials. At 125–500 Hz, α ranges from 0.039 to 0.160; Γ ranges from 2.6×10^{-4}/mm to 3.5×10^{-4}/mm; $R > 0.9$. Silica fume (~0.1 μm) provides interfaces, thereby enhancing α and Γ by 40% and 20% respectively for cement paste (125 Hz), but it does not affect R.

1. Introduction

Sound absorption is needed to alleviate the noise pollution that increasingly erodes the quality of life of most people, particularly those in urban areas and those that work in noisy environments. Transportation (rail, highway and aircraft) is a significant source of outdoor noise.

A common mechanism of sound absorption is the viscous deformation of the solid in response to the sound wave [1–7]. Other mechanisms are the air vibration associated with the sound causing friction between the air and the pore wall of the solid and the multiple reflections of the sound at the wall of the pores [1–7]. The multiple reflections result in the sound traveling for multiple times in various directions in the material, thereby providing an additional mechanism of sound absorption. Sound absorption materials are thus commonly porous soft materials, such as foams [1–7] and textiles [8,9]. Less commonly, biomaterials [7,10] are exploited. The porosity and softness are not desirable for the structural performance.

The most established method of enhancing the sound absorption effectiveness of a material involves the introduction of porosity [1–7], though this is typically at the expense of the mechanical performance. In contrast, this paper investigates the use of solid–solid interfaces in a non-porous material to enhance the sound absorption effectiveness. Although this paper uses cement-based materials to demonstrate the concept of using solid–solid interfaces to enhance sound absorption, the method described in this paper is expected to be applicable to other materials that contain solid–solid interfaces.

From the practical viewpoint, this paper concerns sound absorption materials that are stiff and non-porous, due to the interest in sound absorption materials that are good structural materials. This interest is partly because such a structural material would reduce or even eliminate the need for the use of a soft non-structural sound absorption material in combination of a structural material in order to render sound absorption capability to a structure. This would simplify design and avoid the bulkiness and extra weight associated with the presence of the soft sound absorption material. Furthermore, a structural material tends to be more durable than a soft material. In addition, the large volume of a structural material in a structure enables the structural material to have a large influence on the sound absorption ability of the structure.

Cement-based materials with improved effectiveness for sound absorption are commonly porous [11–17], with the pores introduced by the use of admixtures (e.g., perlite [8]), aggregates, foaming agents or templating methods. Another approach involves

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the incorporation of non-porous admixtures (e.g., cellulose fibers) that inherently have some viscous character [18,19].

The internal solid–solid interfaces in a non-porous solid are to be distinguished from the air–solid interface associated with a porous solid [1–7]. Prior work on sound absorption has emphasized the latter. In contrast, this work uses the solid–solid interfaces in a non-porous cement-based material to enhance the sound absorption effectiveness.

By incorporating silica fume as an admixture in the cement-based material, a large amount of interface area per unit volume is obtained. Silica fume is submicron silica (SiO_2) particles. It is a waste material and a pozzolanic admixture for enhancing the mechanical properties and decreasing the liquid permeability of cement-based materials [20]. These effects relate to the microstructural refinement, which also results in enhanced bonding with steel [21].

Silica fume tends to increase the vibration damping ability of cement-based materials [22]. The damping improvement is attributed to the low-amplitude dynamic slippage that occurs at the interface between silica and the cement matrix during vibration [22]. Damping relates to the viscous behavior, which promotes the sound absorption ability. The effect of silica fume on the sound absorption ability has not been previously addressed, though silica fume was used as an admixture along with perlite for improving the sound absorption ability of cement [15].

Silane acts as a coupling agent between silica and cement. It consists of molecules, with each molecule having desired functional groups at its two ends [23]. Silane treatment has been shown to improve the effectiveness of silica fume for promoting the vibration damping ability of cement-based materials [22], due to the viscous character of the silane molecules and the effect of the silane treatment on the interface between cement and a silica fume particle. Therefore, both silane-treated silica fume and untreated silica fume are used in this work.

Sound intensity (I, in W/m^2) is defined as the sound power per unit area. It is the product of the sound pressure (root mean square sound pressure, in Pa) and the particle velocity (in m/s). For a plane progressive wave, I is given by

$$I = p^2 \Big/ Z, \tag{1}$$

where p is the sound pressure and Z is the characteristic acoustic impedance. In this context, the phase of the sound wave is not considered [24]. The sound absorption coefficient (α) of a material is a quantity that describes how much of the incident sound intensity is not reflected by the material. It is defined as

$$\alpha = I_a / I_i \tag{2}$$

where I_a is the unreflected sound intensity and I_i is the incident sound intensity. Although α values as high as 1.0 have been reported [8], the high values are achieved only over narrow frequency ranges [15].

Although α has been reported for a number of cement-based materials [11–19], the contributions of the various constituents (including the interfaces) to α have not been elucidated. Knowledge of these contributions is valuable for guiding the design of cement-based materials for sound absorption. By systematically measuring α of cement paste, mortar (with fine aggregate, i.e., sand) and concrete (with fine and coarse aggregates, i.e., sand and stones), each with and without silica fume, this work provides the first determination of the contributions of the various constituents and interfaces on α of cement-based materials.

Ultrasound is sound with a frequency above the upper limit of human hearing (i.e., >20 kHz). Typically investigated ultrasonic frequencies exceed 1 MHz. Due to the importance of medical ultrasonography and ultrasonic testing, ultrasonic absorption [25–29] has received much more attention than the absorption of audible sound. Due to medical ultrasonography, most work on ultrasonic absorption is concerned with liquids [25–27], e.g., ferrofluids with $\Gamma = 0.28$/mm at 3.6 MHz [25]. In contrast, this work is limited to sound in the audible range (125–500 Hz).

The objectives of this work are (i) to investigate the use of solid–solid interfaces in a non-porous material to enhance the sound absorption effectiveness, (ii) to provides an analytical model for describing the effects of solid constituents and solid–solid interfaces on the sound absorption, (iii) to investigate and determine the contributions of cement, silica fume and aggregates on the sound absorption coefficient of cement-based materials without introduced porosity, (iv) to characterize the sound absorption behavior of cement-based materials at a level beyond that of prior work, (v) to develop cement-based materials that exhibit enhanced sound absorption without loss of strength due to porosity, and (vi) to strengthen the science base for the design of materials for sound absorption.

2. Methods

The value of α can be measured by either the reverberation chamber method (ASTM C423, also known as the room method) or the impedance tube method (ASTM E1050). In the room method, the sound absorption material under test lines all the surfaces of the room and a diffuse sound field is used, so that the sound has evenly distributed angles of incidence relative to the surfaces of the test material. The room method is commonly used for commercial product evaluation. In the impedance tube method [8,24], sound is emitted from one end of a hollow tube, with the test specimen at the other end of the tube, so that α is measured at normal incidence. This method is commonly used for research and is used in this work.

Upon the incidence of a sound wave on to a solid surface, a part of the sound intensity is reflected by the surface whereas the remaining part enters the solid and becomes absorbed as it travels into the solid. The extent of reflection of the sound at the front and back surfaces of the solid and the extent of absorption of the sound within the thickness of the solid are fundamental to understanding the interaction of sound with the solid. However, this information has not been previously reported in relation to cement-based materials. By measuring α for various thicknesses of the material, this work provides the first determination of the reflectivity R (the fraction of incident sound intensity that is reflected at a surface) and the propagation constant Γ (the distance in the material over which the sound intensity is reduced by absorption by a factor of 1/e) of cement-based materials. The quantity Γ is defined by the equation

$$I = I_o \, e^{-\Gamma x}, \tag{3}$$

where I_o is the incident sound intensity and I is the sound intensity at a distance x beneath the surface of the solid. The absorption loss in dB is given by

$$\begin{aligned} \text{Absorption loss (dB)} &= -20 \log e^{-\Gamma x} \\ &= (20/2.3)\Gamma x. \end{aligned} \tag{4}$$

The Γ is scientifically more meaningful than α, because α depends on both the material and the distance. Values of the parameters Γ and R are practically valuable, as they allow calculation