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Design and numerical analysis of syntactic hybrid foam for superior sound absorption

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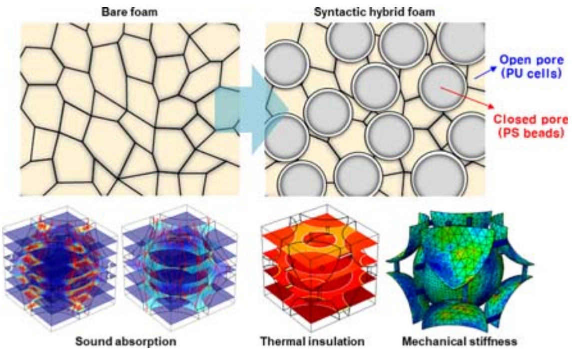
HIGHLIGHTS

- Novel hybrid microstructures were proposed by combining microcellular structure with microbeads.
- The hybrid microstructures enable superior sound absorption performance.
- The hybrid microstructures improve thermal insulation performance.
- Elastic modulus of the hybrid microstructures is much higher than that of the basic foam.

GRAPHICAL ABSTRACT



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ABSTRACT

A microcellular polyurethane (PU) foam is widely used as a sound absorber to eliminate noise by utilizing its complex internal structure. The most intriguing issue for the sound absorbing PU foam is how to reduce density while maintaining or improving the performance. In this study, novel syntactic hybrid foams (SHFs) were designed and suggested by embedding hollow microbeads in the open cell PU foam. Numerical simulation was carried out to predict sound absorbing performance by employing periodic unit cells representing microstructures of a bare foam (BF) and SHFs. It was found from the simulation that the sound damping performance of SHFs was improved significantly by a detoured sound propagating path provoked by the embedded microbeads. The predicted sound absorption performance of SHFs was even superior to that of the bare foam with double density. Furthermore, heat transfer and structural analysis showed that SHFs can provide high thermal insulation and mechanical robustness. It is anticipated that the hybrid microstructure designed in this study will be utilized to develop advanced sound absorbing materials with outstanding sound absorption, thermal insulation, and mechanical stiffness.

1. Introduction

Polyurethane (PU) foams with a porous microstructure are widely utilized for sound absorption [1–5] and thermal insulation [6,7]. Energy fields passing through the porous structure are dissipated or blocked effectively, due to its complex structural nature. Among them, the sound

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absorption capability enhances our quality of life by eliminating troublesome noises. Sound waves propagating through the foam are mainly eliminated by 'visco-inertial and thermal damping' rather than 'visco-elastic damping', because volume of a solid part in the foam is much smaller than that of the air [8,9]. The visco-inertial and thermal damping diminishes acoustic pressure magnitude by viscous friction and thermal exchange on solid-air interfaces [10–12]. Because of the sound damping mechanisms, manipulating and optimizing microcellular structures can induce the improved sound absorption of foams without increasing density or foam thickness [13–16].

Microcellular structures of sound absorbing foams have been optimized to achieve more advanced performance [1,3,4,17–20]. There are two significant structural parameters that affect sound absorbing behavior of the microcellular foam; cell size and cell openness. Park et al. [1] predicted the optimized cell size by carrying out multiscale poroacoustics simulation, and the PU foam having the optimized cell size was fabricated using an ultrasonic foaming method. The same research group [4] also attempted theoretical studies on the optimized cell openness with the same simulation method as above, yielding the best semi-open cell PU foam with superior performance to the double density foam. In addition, various studies have been carried out on the microcellular structure theoretically or experimentally [2,3].

Meanwhile, fabrication of composite foams is another strategy to improve sound absorbing performance [21–26]. Verdejo et al. [21] attempted to enhance acoustic damping by incorporating carbon nanotubes (CNTs) into polyurethane foams. They claimed that CNTs would contribute to sound energy dissipation because of great interfacial friction between CNTs and a matrix. Sung et al. [22] employed nanoclays to increase sound damping. Energy dissipation in a solid frame was increased by the vibrating nanoclays, and greater sound reflection occurred due to the increased stiffness of cell walls. These previous researches about composite foams provided a meaningful pathway to improve sound absorbing performance of polymeric foams. However, the manufacturing strategy of the nanocomposites has focused on the damping property of materials without considering the main mechanism of sound absorption of foams. Therefore, this strategy did not provide an effective method to reduce density of foams or to significantly improve the sound absorption performance of existing foams.

Generally, sound absorbing foam has relatively high density of about 80 kg/m^3 since it needs both certain compressive stiffness and a microcellular structure with sufficiently complex geometry for high tortuosity [1]. On the contrary, the low density open cell PU foams cannot be used as a sound absorber because of poor sound absorbing performance and mechanical vulnerability. The previous study [4] demonstrated that the optimized cell openness can achieve good sound absorption of a low density (40 kg/m^3) foam. However, it is very difficult to precisely control the cell openness with chemical additives, and this method may possibly deteriorate other material properties.

In addition, conventional sound absorbing PU (polyurethane) foams have failed to achieve good performance in thermal insulation since the thermal energy flows facilely through open cell media [7,27,28]. The easy heat flow occurred because the open cell structure allows the convection heat transfer through the open walls. Therefore, development of a lightweight multifunctional foam will be innovative and practical in industrial and academic applications, providing both high thermal insulation and high sound absorption properties simultaneously.

The present work proposes conceptual designs of the unique hybrid microstructures with low density, superior sound absorption, and multifunction. The proposed structures consisted of polystyrene hollow microbeads (40 kg/m^3 density) and microstructure of an open cell PU foam (40 kg/m^3 density). And the proposed designs are named as syntactic hybrid foams (SHFs). Unit cells were constructed to model the geometry of SHFs which contain microbeads and a bare foam (BF) with open cells (40 kg/m^3 density). Multiscale poroacoustics simulation was carried out by solving viscous flow problem, inertial flow problem, and Johnson-Champoux-Allard model equations [11,12]. Sound absorption coefficient curves were obtained theoretically for different unit cells and compared each other. Mechanical and thermal insulation properties of the unit cells of BF and SHF were also investigated numerically, and effective material properties were evaluated.

2. Simulation method

2.1. Multiscale poroacoustics simulation

Numerical simulation for sound absorption was performed by using a multiscale poroacoustics method which consists of a microscale flow analysis and a macroscale acoustical analysis [9,15,29,30]. A commercial finite element program, COMSOL Multiphysics, was employed in this study.

In the microscale analysis, poroacoustics parameters for Johnson-Champoux-Allard (JCA) model were calculated by solving two flow problems in the constructed periodic unit cells (PUCs). In this analysis, the viscoelastic damping due to deformation and vibration of the polyurethane cell structure or polystyrene beads was ignored. The calculated parameters, *i.e.*, flow resistivity (R_f), tortuosity (τ_∞), and characteristic lengths (L_v and L_{th}), represent the geometric feature of microcellular structure of each SHF. Free tetrahedral meshes were incorporated in PUCs and consisted of 1,357,847 domain elements, 268,928 boundary elements, and 15,039 edge elements. The modeling method of PUCs will be described in the Results and Discussion in detail. Stokes' equation is used with boundary conditions for solving viscous flow problems as

$$\mu\nabla^2\boldsymbol{v} - \nabla p = \boldsymbol{g} \quad \text{in} \quad \Omega_\mathrm{f} \tag{1}$$

$$\nabla\cdot\boldsymbol{v} = 0 \quad \text{in} \quad \Omega_\mathrm{f} \tag{2}$$

$$\boldsymbol{v} = 0 \quad \text{on} \quad \Omega_\mathrm{sf} \tag{3}$$

where μ is the viscosity of air, p is the pressure, $\boldsymbol{v}$ is the velocity field, Ω_f is the fluid domain, $\mathbf{g}$ is the constant vector field of pressure gradient throughout the fluid domain, and Ω_sf is the boundary of the solid-fluid domain [31–33]. The velocity field is obtained from the solution of Eqs. (1)–(3). The permeability field ($\boldsymbol{k_0}$) is calculated from $\boldsymbol{k_0} = -\mu\boldsymbol{v}/|\mathbf{g}|$, where $\mathbf{g}$ is the pressure gradient which is constant throughout the whole fluid domain of PUCs. Flow resistivity (R_f) is defined as $R_f = \mu/(<\boldsymbol{k_0}>_f \cdot \epsilon_p)$, where ϵ_p is the porosity [30].

In the multiscale poroacoustics modeling, the inertial flow problem has been replaced by an electrical conduction problem given by the Laplace equation due to its theoretical similarity between the two equations [34]. Electrical conduction equations with boundary conditions [30] are as below.

$$\boldsymbol{E} = -\nabla\varphi + \boldsymbol{e} \quad \text{in} \quad \Omega_\mathrm{f} \tag{4}$$

$$\nabla\cdot\boldsymbol{E} = 0 \quad \text{in} \quad \Omega_\mathrm{f} \tag{5}$$

$$\boldsymbol{E}\cdot\boldsymbol{n} = 0 \quad \text{on} \quad \Omega_\mathrm{sf} \tag{6}$$

where $\boldsymbol{E}$ is the scaled electric field, $\boldsymbol{e}$ is the unit vector field, and $\nabla\varphi$ is the fluctuating part with the scalar field φ [15]. The scaled electric field obtained from the solution of Eqs. (4)–(6) was utilized to evaluate tortuosity factor (τ_∞) and viscous characteristic length (VCL), defined as $\tau_\infty = <\boldsymbol{E}^2>_f / <\boldsymbol{E}>_f^2$ and $\mathrm{VCL} = L_v = 2\int_{\Omega_\mathrm{f}}\boldsymbol{E}^2 \mathrm{d}\Omega_\mathrm{f} / \int_{\Omega_\mathrm{sf}}\boldsymbol{E}^2 \mathrm{d}\Omega_\mathrm{sf}$ [30]. Porosity (ϵ_p) and thermal characteristic length (TCL) were calculated from the volume ratio of the solid/fluid domain and the relationship of $\mathrm{TCL} = L_{th} = 2\int_{\Omega_\mathrm{f}}\mathrm{d}\Omega_\mathrm{f} / \int_{\Omega_\mathrm{sf}}\mathrm{d}\Omega_\mathrm{sf}$.

By using the poroacoustics parameters obtained from the equations above, two frequency-dependent complex values, effective bulk density