Sound Absorption Properties of An Open-Cell Ceramic with A High Occupancy Ratio for Recycling of Sediment from Taihu Lake

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Abstract. This paper proposes an open-cell ceramic acoustic material to combat noise pollution, which utilizes sediment from Taihu Lake as its main ingredient. The open-cell ceramic is manufactured using the gel injection molding method to achieve a high occupancy ratio. Simulation and experimental research demonstrate that the open-cell ceramics possess excellent sound absorption properties, particularly in the middle and high frequencies, with high sound absorption characteristics. The unique pore structure of the open-cell ceramics provides multifunctional and excellent mechanical properties, resulting in a lightweight, pore-designable, and broad-frequency sound absorption material that is environmentally friendly, energy-efficient, and renewable.

Keywords: Taihu Lake sediment; open-cell ceramics; sound absorption coefficient; finite element modeling; gel injection molding; experimental tests.

1. Introduction

Noise pollution is a major global issue, ranking among the top three pollutions along with water and air pollution. It adversely affects human hearing, causing fatigue and impairment, and also accelerates the aging of buildings and structures, compromising equipment precision and lifespan. Passive control is commonly employed for noise pollution using two types of sound-absorbing materials: porous and resonant. However, existing porous materials (e.g., fiber, slag wool, rock wool, glass wool) exhibit limitations in low-frequency sound absorption, environmental impact, lifespan, and suitability for clean spaces. Therefore, there is a pressing need for ecologically-friendly, efficient, and environmentally protective porous materials in practical applications [1]. The densely populated Taihu Lake basin faces severe pollution issues. The large-scale sediment dredging project in the lake generates significant amounts of microorganisms and heavy metals, posing a long-term risk of harmful pollution. Consequently, the disposal of dredged bottom mud presents a solid waste management challenge in the surrounding economic circle. To address this issue, the paper proposes a resource utilization perspective for treating and disposing of dredged bottom mud. This approach aims to return pollutants to nature, enhancing the living environment, including noise control, and alleviating the escalating land resource tension.

To achieve this goal, open-cell ceramics are identified as the optimal candidate materials for their high porosity, corrosion resistance, environmental friendliness, and broad-band high sound absorption capabilities. Up to now, limited work has been focused on the materials field, involving preparation method optimization, improvement of properties through different microstructures, geometric parameters, and composites, as well as the effect of changes in raw material ratios for porous ceramic preparation on sound absorption properties. However, few researches have reported the sound absorption properties of open-cell ceramics and the raw materials used to prepare porous ceramics are relatively expensive, which leads to difficulties in large-scale industrial production and applications. Masayoshi Fuji et al. [2] investigated the effects of surfactants on porous building ceramics' microstructure and some intrinsic properties such as sound absorption and thermal conductivity, which were fabricated by gelcasting. J.H. Chen et al. [3] investigated the effects for processing parameters on the structure of samples, and for the pore size, sample thickness and porosity on the sound absorption performance of samples. Wu [4] fabricated ceramic hollow sphere structures with micro-sized pores and demonstrated the broadband sound absorption properties of these structures. Carlesso [5] prepared the alumina/mullite-based porous ceramics by combining the freeze gelation and sacrificial templating processes. By adjusting the addition of the templates and solid content, they have studied the effect of porosity on the sound absorption properties of the porous ceramics. Chao He et al. [6] proposed a novel hybrid method, which combines pore-forming method with twice-foaming method to produce macro-porous ceramic with excellent sound absorption coefficient at medium and low frequency noise and multimodal pore size distribution. J.X. Sun et al. [7] prepared the cellular ceramic foam by using natural zeolite powder as the main raw material and found that sample thickness is the main factor, air gap depth is the second and both of pore size and porosity would have a relatively slight effect on the performance. The aforementioned results conclusively demonstrate that the physical and mechanical properties of porous materials are contingent upon their microstructures, including pore structure, porosity, pore size, and other factors. In addition, A. J. Otaru et al. [8] reviewed the acoustical properties and characterisation methods of sound-absorbing porous materials and described in detail pore-structure related parameters of soundproofing devices; models used for predicting their acoustic absorption behaviour and techniques for enhancing their sound absorption potential. Particularly, the type made by a replication casting process (i.e. "bottleneck-type" structures as referred to in this work) is presented. Meanwhile, Ningning Yan et al. [9] prepared porous ZrC ceramics with uniform pore distribution using evaporating solvent and hot-pressing sintering. They also investigated the effects of porosity of porous ZrC ceramics on their microstructure, compressive strength, thermal conductivity and sound absorption. Moreover, Marco Caniato et al. [10] proposed and validated a new procedure for tortuosity computation of foam, which perform determination of the parameters of Johnson–Champoux–Allard acoustic model using five different forecasting methods including traditional analytical model for fibrous materials as well as inverse procedure. Therefore, to obtain the controlled-porous is the significate for the sound absorbing materials, especially for the ceramic-based absorbers.

In this study, we synthesized open-cell ceramics using sediment from Taihu Lake as the primary raw material. The gel foaming injection molding technique was employed to achieve high sediment utilization efficiency. Through experiments and simulations, our findings indicate that open-cell ceramics exhibit excellent sound absorption properties across a wide frequency range. Consequently, they represent an environmentally friendly sound absorption material suitable for diverse applications, including building construction, transportation, and other fields.

2. Materials and methods

2.1 Samples preparation

To produce open-cell ceramics, a mixture of dried Taihu Lake sediment powder, auxiliary materials, dispersants, and gelling agents was thoroughly blended. Foaming agents and foam stabilizers were added to the mixture before molding, drying, and sintering, as shown in Figure 1. Anionic and cationic surfactants were combined to ensure adequate foaming. The resulting slurry was poured into a glass beaker, mechanically stirred, and injected into an acrylic mold. After drying and sintering at room temperature, the sample was further treated at 1,500 ℃ for 4 hours. The resulting product is a lightweight open-cell ceramic material characterized by a porosity range of 75 – 85% (corresponding to a bulk density of less than 0.75 g/cm^3), pore sizes between 1 – 7 mm, and a thickness of 15–25 mm. Figure 2 illustrates a sample exemplifying the varying microscopic parameters of the prepared samples.

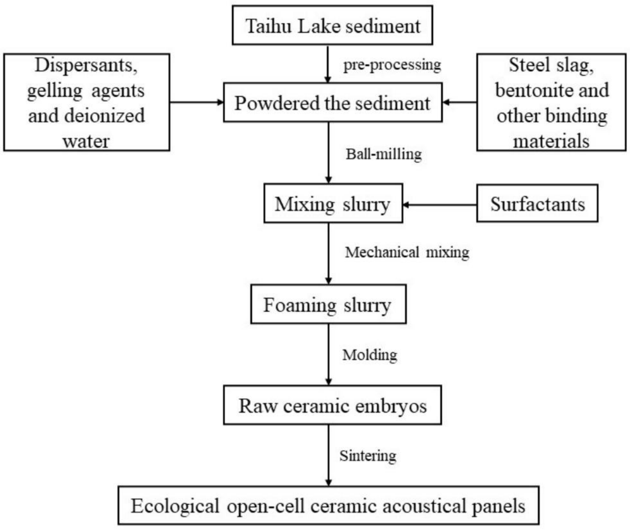

Figure 1 Sketch of gelcasting-foaming process of the open-cell ceramics.

Figure 2 Photograph of the open-cell ceramics after sintering.

2.2 Samples characterization methods

2.2.1 Acoustic experiments

The characterization of sound absorption performance in porous materials primarily relies on the sound absorption coefficient, which quantifies the ratio of absorbed sound energy to the total incident sound energy [11]:

$$\alpha = \frac{E_1 - E_2}{E_1}. \tag{1}$$

E1 and E2 represent the incident and reflected sound energy, respectively, with a unit of dB. Generally, the sound absorption coefficient is between 0 and 1, and it is closer to 1 to indicate a better sound absorption performance.

Two specimens of each type of open-cell ceramic samples with a thickness of 24 mm were tested (Figure 2). Cylindrical samples with diameters of 98 mm and 28 mm were manufactured and underwent acoustic parameter measurements, including absorption coefficient and impedance, following ISO 10534-2:1998(E) standards. The measurements were performed within the frequency range of 50 Hz to 6300 Hz using a sine swept signal. Impedance tubes with diameters of 100 mm and 30 mm were employed for the measurements. The experimental setup consisted of a hard backing configuration with two microphones and a loudspeaker serving as the noise source (Figure 3).

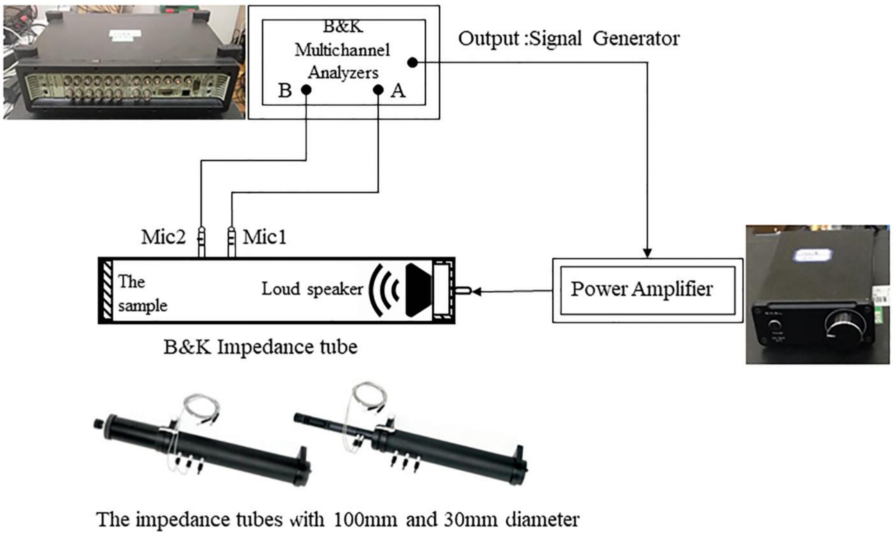

Figure 3 Experimental measurement system developed for the transfer function two-microphone method of normal incidence absorption coefficient.

2.2.2 Acoustic numerical simulation

Open-cell ceramics are widely acknowledged for their outstanding sound absorption properties, leading to their extensive utilization in both industrial and civil applications. These ceramics find applications in panels for mitigating noise in interior and exterior habitable spaces, as well as in walls, partitions, false ceilings, bulkheads, doors, and other relevant areas. Nevertheless, designing these intricate composite microstructures is a time-consuming and costly process, involving multiple tests, validation procedures, and the production of diverse samples with varying configurations. Therefore, the availability of forecasting systems based on numerical or computational models becomes crucial and highly desirable across all disciplines of applied acoustics.

Presently, the Johnson-Champoux-Allard (JCA) model demonstrates exceptional capability in accurately predicting the frequency response across the entire audible range. This model is determined by five non-acoustic parameters: flow resistivity (σ), porosity (ϕ), tortuosity (α_∞), viscous characteristic length (Λ), thermal characteristic length (Λ'). The parameters of the acoustic model were computed using experimental data, such as SEM measurements. These computed parameters were then used as input values for calculating the acoustic absorption coefficient. The rationale for employing these analytical models lies in their widespread use and simplicity as predictive equations documented in the literature. Therefore, it is crucial to investigate their applicability to open-cell ceramics. In the event that this assumption is not validated, potential reasons for their failure will be proposed.

In practical applications, porous acoustic materials often exhibit non-ideal cylindrical voids and non-uniform alignment, thereby requiring the adjustment of the parameters associated with them. Straight pores require adjustment with the tortuosity α_∞, while the effects of fluid medium viscous forces and heat transfer necessitate correction using the viscous characteristic length Λ and the thermal characteristic length Λ', respectively. These corrections are crucial in order to effectively model the acoustic properties of porous materials. The modified Johnson-Champoux-Allard (JCA) model is described below:

$$\boldsymbol{\rho = \alpha_\infty \rho_0 \left[1 + \frac{\sigma\phi}{j\alpha_\infty \rho_0 \omega}\sqrt{1 + \frac{4j\alpha_\infty^2 \rho_0 \omega \eta}{\sigma^2 \phi^2 \phi^2 \Lambda^2}}\right]}. \tag{2}$$

$$\boldsymbol{K=\gamma P_0\left[\gamma-\frac{\gamma-1}{1+\frac{\sigma\phi}{jB^2\omega\rho_0\alpha_\infty}\sqrt{1+\frac{4j\alpha_\infty^2\eta\rho_0\omega B^2}{\sigma^2\Lambda'^2\phi^2}}}\right]^{-1}}. \tag{3}$$

Where, is the equivalent density of the fluid medium, K is the bulk elastic modulus, ρ_0 is the air density, σ is the flow resistivity of the porous material, ϕ is the porosity, α_∞ is tortuosity, ω is the acoustic angular frequency, Λ is the viscous characteristic length, Λ' is the thermal characteristic length, η is the fluid shear viscosity, γ is the air specific heat ratio, and B is Planck's constant.

Furthermore, the propagation constant can be derived from the following equation:

$$\boldsymbol{\Gamma(\omega)=i2\pi f[\rho(\omega)/K(\omega)]^{1/2}=\alpha+i\beta}. \tag{4}$$

$$\boldsymbol{Z(\omega)=[\rho(\omega)K(\omega)]^{1/2}=R-iX}. \tag{5}$$

With the appropriate characteristic impedance and propagation constants, the impedance $\boldsymbol{Z_s}$ for a rigid backing thickness of $\boldsymbol{l}$ can be accurately determined using the following equation:

$$\boldsymbol{Z_s=Z(\omega)coth\Gamma(\omega)l}. \tag{6}$$

If the equivalent impedance of a micro-opened ceramic surface matches that of air, i.e., $\rho_0 c_0 = 1$., the structural absorption coefficient $\boldsymbol{\alpha}$ with an equivalent impedance of Z_s can be expressed according to the acoustic principle:

$$\boldsymbol{\alpha=1-\left|\frac{Z_s-1}{Z_s+1}\right|^2}. \tag{7}$$

3. Results and discussion

Open-cell ceramics exhibit broad-spectrum sound absorption properties and are primarily composed of a thin solid matrix interspersed with air, which creates the air porosity. This distinct microstructure is accountable for the sound absorption capabilities exhibited by the ceramics. The dissipation of sound waves within these materials is primarily attributed to the interaction between the fluid and the structure, taking into consideration the viscosity and thermal properties. Consequently, energy is partially transmitted and absorbed by the fluid, as well as partially by the rigid material encompassing the porosity. Extensive research has been conducted to refine the model, addressing various aspects such as Pannetton's modification [12] on JCA model concerning the pliable frame and Kino's models [13]. However, there is a lack of convincing evidence regarding the agreement between predicted and measured values for intricate open-cell ceramics, with the exception of polyurethane ceramics.

A commercial finite element software, COMSOL Multiphysics, was used to implement this numerical model. The JCA model was evaluated using both mathematical analysis and finite element calculation with COMSOL Multiphysics (Figure 5). The results obtained from both methods exhibited excellent agreement, providing strong confirmation of the accuracy of the finite element model. These findings indicate the high reliability of finite element simulation calculations, positioning them as valuable tools for validating future research findings while minimizing the requirement for extensive experimental work.

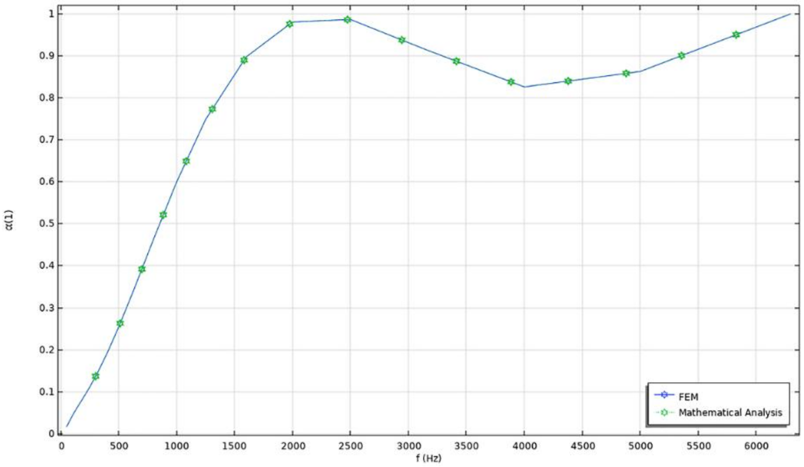

Figure 5 Comparison between finite element calculations using the JCA model (represented by the solid blue line with markers) and mathematical analytical calculations (represented by the green dashed line with markers) for open-cell ceramics.

Following the guidelines outlined in ISO 10534-2:1998(E), the sound absorption coefficients of two distinct open-cell ceramic materials, characterized by varying ratios of raw materials and thicknesses, were measured using the double microphone method in a 30 mm diameter impedance tube (Figure 4). Based on the experimental findings, it can be inferred that the open-cell ceramic material proposed in this study demonstrates exceptional acoustic absorption performance across a wide frequency range. The experimental measurements indicate that the average absorption coefficient of the open-cell ceramics in the frequency range of 50-6300 Hz is approximately 0.8. Within the range of 1000-2000 Hz, the highest absorption coefficient approaches 1. Furthermore, in the range of 2000-4000 Hz, the absorption coefficient slightly decreases but remains above 0.7, after which it rises to over 0.8. These results highlight the broadband sound absorption characteristics of the material. The sound absorption performance of the open-cell ceramics is influenced by different preparation parameters, allowing for the adjustment of the absorption curve's peak within a specific range. Obtaining direct measurements of all fluid phase parameters, such as airflow resistivity, open porosity, tortuosity, viscous and thermal lengths, necessitates the utilization of a comprehensive set of test rigs and can pose challenges in terms of feasibility. Consequently, in this study, we concentrate on investigating the parameter backpropagation approach based on the JCA model. The aim is to compare the results with the directly measured values of microscopic parameters in open-cell ceramic materials, thereby verifying and enhancing the accuracy of parameter prediction. Furthermore, this research aims to achieve the parameterization of open-cell ceramics.

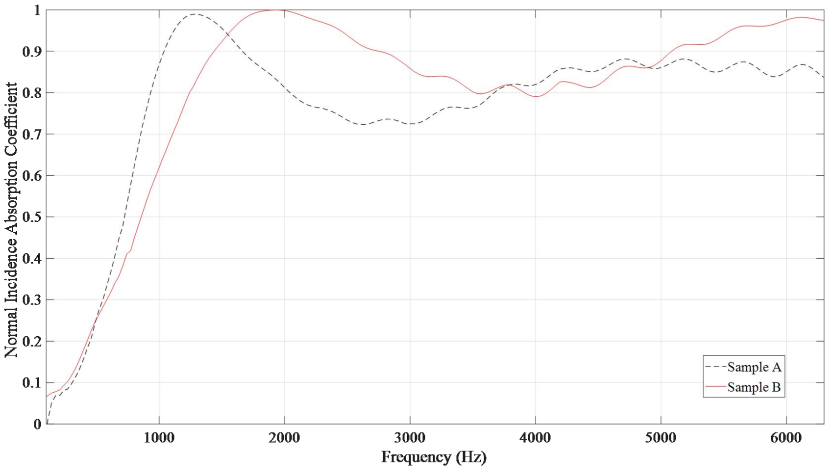

Figure 4 The sound absorption coefficients (frequency range: 50~6300Hz) of open-cell ceramics with different ratios were prepared by the gel foam injection method (the thickness of sample A was 25mm, and the thickness of sample B was 23mm).

4. Conclusions

An open-cell ceramic acoustic material was fabricated using the gel foam injection molding method, demonstrating its potential to effectively utilize sediment from Taihu Lake. This approach offers an opportunity to address sediment storage concerns and promote resource circulation. Through the application of the JCA acoustic model, this study validates the accuracy of both analytical and finite element models, laying a foundation for future investigations on open-cell ceramic acoustic materials. In addition, the sound absorption properties of the open-cell ceramic materials were thoroughly examined using three distinct methods: analytical calculations, FEM simulations, and experimental measurements. Two variations of open-cell ceramics, prepared with different parameters, were subjected to analysis. The results confirmed the accuracy of the JCA model in characterizing porous hard skeletal materials and provided a solid basis for future researches. The experimental measurements showcased the exceptional broadband sound absorption performance of the open-cell ceramics proposed in this study, with an average absorption coefficient of approximately 0.8. This environmentally friendly sound absorption material holds significant research and application prospects, making it highly suitable for practical engineering applications.

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