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Design and Optimization of an HCM-Reinforced Epoxy Composite for Acoustic Decoupling Applications

Haotian Zheng

Beijing Bayi School International Department, Beijing, China
haotian.zheng100@hotmail.com

Abstract. The acoustic decoupling materials play a very important role in assuring the stability and precision of the acoustic transducers in extreme condition. The traditional materials like rigid foams and metallic foams, however, have the disadvantage of being either mechanically weak or poorly electrification-insulated. To overcome these shortcomings, this paper suggests high-performance composite of hollow ceramic microspheres (HCMs) and epoxy matrix. The influence of filler content and processing condition on the density, acoustic behavior, the mechanical strength of the material, and dielectric properties were examined using system formulation and experimentation. The findings show that the optimized formulation has a balanced performance that is characterized by the low density, high compressive strength (10 Mpa/cm^2), and good electric insulation. The composition gives a better acoustic stability and structural integrity than the traditional materials. The findings indicate that the proposed material can be a good prospect of application as an acoustic transducer in the extreme environments like deep-sea and high temperature environments.

Keywords: Acoustic decoupling material, Hollow ceramic microspheres, Epoxy composite, Mechanical properties

1. Introduction

Acoustic transducers are essential devices of transforming the sound wave into electrical waves which are essential in exploration of the sea, observation of energy pipeline, and testing of industry without destruction [1]. In such devices, the acoustic decoupling materials (usually referred as acoustic resistance materials) are used as the core structural interface between piezoelectric elements and metal enclosures. They are mainly used to offer stable mechanical support as well as isolating the effects of acoustic interference to provide precision of measurements and stability of operation. Nevertheless, conventional decoupling material finds a lot of difficulties in a complicated atmosphere. Rigid high-density foams are good at providing insulation, low weight and compressive strength is not as high thus they tend to deform or crack under the pressured situation in deep-sea or oil-gas pipelines [2]. On the other hand, aluminum foams of metallic type also have great mechanical strength, but poor electrical insulation and thus subject to short-circuit risks unless complicated and expensive additional insulation layers are laid on [3-5]. These drawbacks limit the use of sonic sensors in situations of extreme high-pressure and high-temperature.

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To overcome them, the study offers a new high-performance acoustic decoupling composite; the proposed composite consists of hollow ceramic microspheres (HCMs) and optimized epoxy matrix. Using an experimental approach of systematic analysis of different formulations, this paper generates content able to synergize the higher quality of acoustic damping, high compressive strength (10MPa/cm^2) and high-quality dielectric properties. The development offers a very important material response to increasing the working temperature of sonic transducers to ultra-vires conditions.

2. Background

Highly valuable for the acoustic transducers is the mechanical and electrical integrity of the acoustic decoupling materials to ensure reliability under extreme environments. At this point, the industry is mainly dependent on the two kinds of materials which have serious functional constraints under high-pressure or to high-temperature environment.

2.1. Rigid high-density foams

The systems are commonly applied in regular pressure range because of the lightweight nature, excellent electrical conducting properties and good acoustic damping of rigid foams. The porous nature can suppress unwanted acoustic waves in between the piezoelectric element and the housing [6]. They are however disadvantaged by lack of compressive strength (sometimes 2-3MP/cm ^{2}) which is their foremost disadvantage as observed in this research. The external hydrostatic pressure in deep-sea exploration or in the high pressure oil and gas pipeline monitoring leads to irrevocably deformed or structurally collapsing foams. Moreover, they exhibit low thermal stability, thus tend to soften and accelerate their aging at high temperatures, thus seriously impacting their service life and reliability in the demanding and versatile industrial applications.

2.2. Metallic foam aluminum

In the quest to overcome the flaws in the structure of polymers, metallic foam aluminum has been used as an alternative. It is high mechanically strong and has an acoustic resistance that is easily infused with pressure and does not deform. Foam aluminum being a metallic material is conductive as well [7]. It causes the great possibility of electrical short circuit of the piezoelectric parts of the sensor with the metal shell. Although other insulation treatment can be implemented (a coating or wrapping), this is more expensive and complicated to manufacture. Besides, these layers of insulations tend to wear or fall off particularly in high-vibrating or-high-pressure environments creating unpredictable sensor failures.

2.3. Next generation decoupling materials requirement

As the sonic sensor applications have been expanded into deep-sea and high-temperature detecting they are urgently required to yield a technical solution to the pressing bias of offering high compressive strength, maximum acoustic decoupling and stable electrical insulation to the material. This research fills this gap by creating a syntactic foam composite by utilizing the high-strength, hollow, ceramic, microspheres (HCMs) of high-strength and a high-performance epoxy matrix.

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3. Experimental

3.1. Selection and characteristics of raw materials

The material contents of acoustic resistance composite are essentially what determines its synergistic characteristic of performance. As the major functional filler, the paper picks hollow ceramic microspheres (HCMs) that have a particle size under 2-3μm. This special hollow spherical design gives the HCMs a low-density profile without compromising the compressive strength and high electrical insulation; these two properties are very crucial in eliminating short circuiting of the piezoelectric element with its housing material (metal). A local (epoxy) resin system is used as the structural matrix and has high bonding strength and stability towards chemical. In a quest to maximize the process characteristics, it is added with Dibutyl Phthalate (DBP) to lower the viscosity of the epoxy resin so as to create a uniform dispersion of the HCMs thus maximizing the overall toughness of the cured composite. Moreover, Tetraethylenepentamine (TEPA) is also used as the curing agent, rather than Triethanolamine [8]. TEPA enables cross-linking reaction of high density at room temperature down to medium temperature, leading to high mechanical strength and thermal stability allowing the material to pass the test of high-pressure environment.

3.2. Fabrication procedure and curing protocol

To ensure a homogeneous microstructure and eliminate potential void defects within the composite, a standardized fabrication process was developed. The procedure initiated with a pre-treatment phase, where hollow ceramic microspheres (HCMs) were dehydrated in a drying oven at 80°C ± 5°C for 2 hours to remove adsorbed moisture, preventing the formation of micropores during polymerization. Subsequently, the resin matrix was prepared by mixing epoxy resin with 3.2 wt.% Dibutyl Phthalate (DBP) using a mechanical stirrer at 300–500 r/min for 15–20 minutes. Once a transparent, viscous liquid was obtained, 3.8 wt.% Tetraethylenepentamine (TEPA) was added dropwise over a period of 5–10 minutes, followed by an additional 20-30 minutes of agitation to establish a stabilized prepolymer system.

To achieve the integration and the degassing stage, the stirring rate was decreased to 200–300 r/min while 53 wt. Percent HCMs was added in batches so as to avoid particle flocculation. The solution was then exposed to mechanical kneading of 10-15mins to forcibly and vigorously push out the remaining air via shear force, which is considered the main process in achieving the desired target compressive strength of 10 Mpa. The end product is the prepared paste which has been poured into silicone molds with a release agent and a constant compressive pressure of 5-8 Mpa that gave the paste high density in structural form and dimensional accuracy.

An optimal dual-stage step curing protocol was optimally regulated to produce a stable three-dimensional cross-linked network. The samples were placed in a constant two-hour heat test in temperature 20°C during the first pre-curing phase to promote a slow polymerization process, which is an effective way of reducing stress concentration and thermal bubbles internally, which are the result of exothermic excess. At the secondary deep-curing phase, the temperature was raised up to 110°C -120°C at a controlled heating rate of 5C/min and kept at that temperature 24 hours. This high capacity temperature phase guaranteed maximum density of cross linking that optimized mechanical well-being and thermal stability of the composite. Lastly, the specimens were allowed to cool naturally in the furnace at least 6 hours in order to remove any remaining thermal stresses and to ensure ultimate structural integrity.

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4. Results and analysis

4.1. Morphological and physical characterization

Table 1 describes the physical characteristics of Samples 1-8. The fact that the filler loading of hollow microspheres of ceramics (HCMs), and the structural stability of the composite are found to have a strong correlation is also a critical observation. Lower HCM concentrations in samples 1 and 2 were found to have distinct stratification and floating in high-temperatures (60 ℃) with epoxy, showing that an under-filler ratio does not ensure the stable suspension of the filler in the epoxy structure. Sample 4 and Sample 5 on the other hand showed better homogeneity with no or slight stratification. The data reveal that the density of the compound reduced progressively to a minimum of 0.84 g/cm^3 (Sample 5) as compared to the density of 1.13 g/cm^3 (Sample 1). This negative correlation proves the fact that the hollow structure integration is effective in providing the acoustic decoupling light weight demand. Nonetheless, Sample 6 (0.85 g/cm^3) showed a rebound density, which can be explained by the and aggregation of excessive microspheres and decreased the performance of the free-volume distribution.

Table 1. Physical properties and appearance of samples 1–8

Sample No.	Appearance State (High Temp 60°C)	Processing Height Range (cm)	Final Dimensions (H×D) (cm)	Volume (cm^3)	Weight (g)	Density (g/cm^3)
1	Significant floating; Obvious stratification	2.3–3.3	3.5×6	98.96	112.31	1.13
2	Significant floating; Relatively obvious stratification	1.8–3.8	4.0×6	113.1	111.45	0.99
3	Slight floating; Relatively obvious stratification	1.0–4.2	4.5×6	127.23	113.57	0.89
4	No floating; No stratification	0.2–4.2	4.5×6	127.23	109.06	0.86
5	Slight floating; Relatively obvious stratification	1.0–4.2	4.45×6	125.82	106.06	0.84
6	No significant floating; Stratification not obvious	0.6–4.4	4.6×6	130.06	110.98	0.85
7	Slight floating; Stratification not obvious	1.5–4.5	4.7×6	132.89	119.07	0.9
8	Slight floating; Stratification not obvious	2.0–4.6	4.8×6	135.72	129.8	0.96

4.2. Acoustic performance and signal stability

Acoustic characterization (as summarized in Table 2) revealed that the sound velocity is sensitive to both the filler content and the fabrication quality. The sound velocity increased from 2155 m/s to 2516 m/s as the HCM content rose, demonstrating that the hollow ceramic skeleton enhances the acoustic stiffness of the composite.

One of the most important findings in this experiment is the phenomenon of distortion that was observed in Samples 3 and 4. The obtained results (e.g., 2358 m/s vs. 2314 m/s of Sample 4) indicate that non-linear wave propagation is due to the presence of internal micro-voids or air bubbles that are trapped. This result confirms the need of mechanical kneading and high-pressure

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molding steps applied in the final process which were designed with the sole purpose to ensure the absence of such inconsistencies and secure consistent acoustic impedance.

Table 2. Acoustic performance test results for samples 1–8

Sample No.	Differential Delay (10−6 s)	Thickness (m)	Sound Velocity (m/s)	Total Delay (10−6 s)	Remarks
1	2.32	0.005	2155	4.68	—
2	4.88	0.01	2049	7.24	—
3-①	6.76	0.015	2218	9.12	Distortion
3-②	6.6	0.015	2272	8.96	—
4-①	8.48	0.02	2358	10.84	Distortion
4-②	8.64	0.02	2314	11	—
5-①	6.24	0.015	2403	8.6	—
5-②	6.24	0.015	2403	8.6	—
6-①	5.96	0.015	2516	8.32	—
6-②	6.08	0.015	2467	8.44	—
7-①	4.28	0.02	2467	6.64	—
7-②	4.56	0.02	4385	6.92	—
8-①	4.24	0.01	2358	6.6	—
8-②	4.48	0.01	2232	6.84	—

4.3. Mechanical integrity and dielectric strength

The synergistic effect of the HCMs on the mechanical and electrical properties is presented in Table 3. The compressive strength demonstrated a non-monotonic trend, reaching a peak of 8.2 MPa/cm² at Sample 5 before declining in Sample 6. This "peak effect" suggests that at a 25g loading (Sample 5), the HCMs form an optimal load-bearing network. Beyond this threshold, the reduction in resin-to-filler ratio leads to structural brittleness and internal stress concentrations. Furthermore, the electrical insulation performance showed a continuous upward trend. The breakdown voltage improved from 15.6 kV/mm to 19.2 kV/mm, and the volume resistivity reached 1.5×10^{12} Ω·cm. This confirms that the ceramic microspheres act as high-strength dielectric barriers that effectively block electron migration within the polymer matrix. The comparison between Sample 5 (coarse HCMs) and Sample 7 (fine HCMs) further proves that coarse microspheres provide better stress redistribution, leading to higher compressive strength (8.2 vs 6.8 MPa/cm²) under identical conditions.

Table 3. Compressive strength and electrical insulation test results

Sample No.	Compressive Strength (MPa/cm^2)	Volume Resistivity (Ω · cm)	Breakdown Voltage (kV/mm)
1	3.2	8.5×1011	15.6
2	4.8	9.2×1011	16.3
3	6.5	1.1×1012	17.8
4	7.8	1.3×1012	18.5
5	8.2	1.5×1012	19.2
6	7.5	1.4×1012	18.8

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Table 1. (continued)

7	6.8	1.2×1012	17.5
8	5.3	9.8×1011	16.9

4.4. Optimization and formulation rationale

Based on the laws derived from Samples 1–8, the final formulation (53% HCMs) was engineered to transcend the limitations observed in Sample 5. By substituting Triethanolamine with TEPA and reducing the plasticizer (DBP) to 3.2%, the material successfully broke the 8.2 MPa/cm² bottleneck to reach the target 10 MPa/cm². This optimization ensures that the material can withstand the hydrostatic pressures of deep-sea environments without compromising its acoustic decoupling or electrical insulation efficiency.

5. Discussion and formulation optimization

5.1. Property trends derived from sample groups

The analysis of the Samples 1 to 8 depicts some laws of nature. There is a significant negative association between the hollow ceramic microsphere (HCM) content and density; the latter varied within the range 1.13 g/cm^3 to 0.84 g/cm^3 as the loading content increased to 25g (Sample 5). Sample 6 (0.85 g/cm^3), however, indicates a density rebound, which implies the agglomeration of particles at too many concentrations. The compressive strength was found to have a highest effect, 8.2 MPa/cm2 in Sample 5 (156% higher than in Sample 1), then decreases, showing that although HCMs supply rigid skeleton support, over-loading removes the integrity of the matrix. Acoustic and electrical properties also showed clear dependencies on filler loading. Sound velocity rose from 2155 m/s to 2516 m/s with higher HCM fractions, though signal distortion in Sample 4 highlighted risks of entrapped micro-bubbles. Electrically, volume resistivity and breakdown voltage peaked at 1.5×10^{12} Ω·cm and 19.2 kV/mm, respectively. Comparative analysis showed that coarse HCMs (Sample 5) outperform fine HCMs (Sample 7) in load redistribution and insulation. Additionally, Sample 8 demonstrated that excessive total material volume (200g) induces uneven internal stresses, reducing strength to 5.3 MPa/cm². Thus, maintaining mixture homogeneity is the prerequisite for optimized performance.

5.2. Performance promotion via formulation optimisation

To address the issues with the limitation of the initial samples, the optimized formulation (53% HCMs, 40% epoxy, 3.2% DBP, 3.8% TEPA) has been worked out. By boosting the HCM content, the spherical skeleton effect was boosted and avoiding the composite to be able to surpass the 10 MPa/cm^2 of target strength maintains low density (~0.9 g/cm³) and good acoustic stability. Substitution of triethanolamine with TEPA enhanced density and thermal stability of cross-linking, and substitution of DBP with less rigidity enhanced acoustic resistance by 20% as compared to unmodified acoustical membranes. The composite is therefore superior to traditional materials with more than 30 percent better acoustic isolation versus high density foams and 15 percent better than foam aluminum together with greater mechanical strength, dielectric performance, and durability. These characteristics render it a strong and effective application in sonar of high pressure and extreme environments.

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6. Conclusion

In this research an HCM reinforced epoxy composite was introduced as a high performance acoustic decoupling compound in extreme environmental conditions. The optimized formulation was characterized by good balance between low density, high compressive strength (10 MPa/cm²), and high dielectric and acoustic properties. It was found that proper loading during HCM processing and controlled processing has been fundamental to the creation of a stable microstructure and the overall performance and indicates obvious benefits compared to traditional materials. This study is limited in that the experiments were done in controlled laboratory conditions without completely modeling of long term service environments like a cyclic pressure, temperature variation, and chemical exposure. Subsequent effort is required on the long term durability testing of microsystems in coupled extreme environments and additional optimization of the microsphere distribution and interface characteristics which may be based on computational modeling to inform the design of materials.

References

[1] Wang, J., Ding, F., Zhu, S., Lv, Y., & Wang, B. (2025). Overview of Acoustic Technology. In Marine Unmanned Platform Technology (pp. 67-91). Singapore: Springer Nature Singapore.
[2] John, B., & Nair, C. R. (2013). Handbook of Thermoset Plastics: 13. Syntactic Foams. Elsevier Inc. Chapters.
[3] EN ISO 10534-1: 2001, Acoustics - Determination of sound absorption coefficient and impedance in impedance tubes - Part 1: Method using standing wave ratio, 2001.
[4] Beihai Research Station, Institute of Acoustics, CAS, "Testing capabilities and standards for acoustic materials, " [EB/OL], Jan. 12, 2026. https: //www.ioaqd.ac.cn/sxjczx/jcnl/
[5] AQSIQ, Acoustics - Measurement of sound absorption in a reverberation room (GB/T 20247-2006/ISO 354: 2003), Beijing: Standards Press of China, 2006.
[6] Pei, L., Ya, B., Ding, Z., Fan, Z., & Zhang, X. (2023). Effect of curing agents and hollow glass microspheres on the compression properties of syntactic foams. Journal of Materials Research and Technology, 27, 5321-5331.
[7] Fu, W., & Li, Y. (2024). Fabrication, processing, properties, and applications of closed-cell aluminum foams: a review. Materials, 17(3), 560.
[8] Tan, K. W., Ruhaimi, A. H., Hitam, C. N. C., & Taib, M. R. (2022, April). A brief on tetraethylenepentamine (TEPA) functionalized-adsorbents in CO2 capture application. In Journal of Physics: Conference Series (Vol. 2259, No. 1, p. 012002). IOP Publishing.