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Review

Porous Ceramic Microspheres for Enhancing Acoustic Absorption of Polyurethane Foams in Automotive NVH Control

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Abstract

Addressing the persistent challenge of lightweight automotive NVH control, this review critically assesses advances in embedding porous ceramic microspheres into polyurethane foams, establishing their efficacy as a high-performance, low-density solution for acoustic packages. We quantify the mechanistic interplay between visco-inertial and thermal losses and key microstructural levers – open porosity, flow resistivity, tortuosity, and cell size/distribution – demonstrating how these hollow inclusions nucleate finer, more uniform cells and introduce crucial internal interfaces, optimizing acoustic impedance. Evidence from impedance-tube studies confirms performance enhancement: lightweight spheres consistently yield high-frequency response gains (≈ 2 – 4 kHz), achieving absorption improvements of ~ 30 – 50 % at 3.5 kHz, while heavier or larger inclusions enable a strategic frequency shift toward 0.5 – 1 kHz via localized resonance and inertia effects. We conclude that acoustic performance is non-monotonic with filler loading; specifically, modest filler fractions optimize broadband behavior and damping, whereas excessive contents stiffen the polymer frame, promote particle agglomeration, and diminish sub-kilohertz response. Crucially, the rigid ceramic shells provide multifunctional advantages, reinforcing cell walls to increase compressive strength (e.g. from 3.33 MPa to 5.68 MPa), and raising thermal/flame robustness without incurring significant mass penalties. These attributes make the composites highly attractive for critical NVH components such as headliners, pillars, engine covers, wheel-well liners, and emerging EV assemblies. Processing challenges – including dispersion control and balancing openness versus flow resistance – are analyzed alongside opportunities in hybrid micro-nano architectures, property grading through thickness, and model-guided optimization that fuses multiscale structure-property predictions with rapid impedance-tube screening under packaging constraints. This approach has already demonstrated optimal weighted Sound Transmission Loss (STL) reaching 14.02 dB at a thickness of 1 mm, proving the platform's capacity for thin, high-performance NVH solutions. Finally, manufacturability, cost, and sustainability are addressed, noting the appeal of waste-derived cenospheres and compliance pathways (e.g. FMVSS-302), alongside humidity/temperature aging and recyclability. Ultimately, the literature indicates that well-designed microsphere-filled foams can complement or reduce heavy barrier layers, enabling lighter, thinner acoustic packages aligned with emerging EV sound quality targets and durability.

Keywords: Flow resistivity, tortuosity, cell morphology, local resonance, impedance tube

I. Introduction

Noise, vibration, and harshness (NVH) is a critical concern in automotive design, as excessive cabin noise and vibrations significantly impact passenger comfort and perceived vehicle quality [1]. To mitigate airborne noise, lightweight porous materials – especially polyurethane (PU) foams – are extensively used as sound absorbers in vehicles due to their high acoustic efficiency per weight [2]. PU foams dissipate sound energy by viscous friction and thermal exchange as air oscillates through their cellular pores, converting acoustic energy into heat [3]. However, conventional foams face challenges in providing broadband absorption, particularly at lower frequencies, without increasing thickness or adding heavy barrier materials. Moreover, pure polymer foams can suffer from limited thermal stability and may lose effectiveness over time due to mechanical creep or pore structure deformation under load.

Researchers have sought to enhance PU foam performance by modifying its composition and microstructure. Broadly, two strategies have emerged: (1) chemical modifications of the foam matrix and (2) incorporation of fillers into the foam [4]. The first approach involves altering the polymer chemistry to produce foams with tailored cell sizes or open-cell content. For example, varying catalyst types can yield distinct cellular structures that improve sound absorption at certain frequencies [5]. Gwon *et al.* [1] reported that optimizing the foam's cellular morphology via catalyst selection significantly changed

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the absorption behavior. Similarly, adjusting the polymer composition was shown to stabilize cell structures and enhance acoustic damping in rigid foams [6]. The second approach – adding fillers – introduces solid or hollow inclusions into the foam. Fillers ranging from nanoparticles and fibers to micro-scale particles have been used to tune foam properties [7]. In many cases, fillers provide additional energy dissipation mechanisms or alter the foam's pore structure in favorable ways. For instance, the inclusion of a small amount (~ 1 wt%) of magnesium hydroxide nanoparticles in a PU foam was found to dramatically increase sound absorption by increasing open porosity and damping losses [8]. Likewise, adding fibrous fillers can introduce frictional damping and flow resistivity, improving acoustic performance at mid-high frequencies [9]. Each modification strategy has merits, but the focus of this review is on a particularly promising class of fillers – porous ceramic microspheres – and how they synergistically enhance the acoustic absorption of PU foams for automotive NVH applications.

Porous ceramic microspheres are lightweight, often rigid spherical particles with an internal porous structure or hollow core. Examples include fly-ash cenospheres, hollow glass microspheres, and synthetically made ceramic microballoons of materials like alumina or silica [10]. These microspheres are attractive for composite design because they combine low density with high compressive strength and heat resistance [11]. In the context of acoustics, porous microspheres offer a way to introduce additional air cavities and interfacial surfaces within a foam, potentially increasing sound energy dissipation via multiple scattering and enhanced viscous friction [12]. Their rigid ceramic shells can also reinforce the foam's cell walls, counteracting the stiffness loss that often accompanies high-porosity foams. Furthermore, since many microspheres are derived from industrial waste, their use in polymers aligns with sustainability and cost-effectiveness goals [13]. Given these advantages, the incorporation of porous ceramic microspheres into PU foams has gained significant research interest in the last decade as a novel route to improve acoustic absorption without a weight penalty – a key requirement in automotive NVH control. To better illustrate these mechanisms, Fig. 1 schematically depicts the role of porous ceramic microspheres in PU foams for acoustic absorption. While broader reviews have addressed the general pursuit of multi-functional PU foams and the damping properties of polymer composites, a systematic synthesis focused specifically on the synergistic acoustic and multi-physical effects achieved via porous ceramic microspheres remains absent. Existing literature often analyzes these fillers based on isolated properties or within non-automotive contexts, overlooking the critical trade-offs between acoustic gains, mechanical reinforcement, and thermal performance that are paramount for demanding NVH applications. Notably, there is a lack of critical comparison and debate surrounding the dual mechanisms that govern the acoustic response across different frequency bands when varied ceramic sphere types are used. This gap necessitates a dedicated review that integrates materials science, acoustic physics, and NVH engineering constraints to guide future material design.

To ensure comprehensive coverage and minimize selection bias in this critical review, a structured search strategy aligned with PRISMA scoping principles was employed. The search strategy was designed to synthesize research published within the period demonstrating significant growth and technological relevance in the field (January 2014 to December 2024). The focus was placed on experimental and theoretical studies concerning the acoustic and associated mechanical enhancement of polyurethane foams using porous ceramic or equivalent hollow microsphere fillers. Literature identification utilized three major scientific databases recognized for their deep coverage of materials science and engineering: Web of Science Core Collection (WoS), Scopus, and Engineering Village. The primary search aimed to identify specific composite systems and their acoustic properties, while a secondary search ensured coverage of the foundational physics of porous sound absorption. The screening process involved the removal of duplicates, followed by title and abstract screening to ensure strict relevance to automotive NVH requirements and the inclusion of porous ceramic elements. Full-text assessment verified that core acoustic data (absorption vs frequency curves, flow resistivity data) were present, enabling qualitative comparison and synthesis necessary for this critical review.

This review critically examines the state-of-the-art in ceramic microsphere-filled PU foams for sound absorption. We first overview the characteristics of porous ceramic microspheres and their influence on foam microstructure. Next, the fundamental mechanisms of sound absorption in PU foams are discussed, highlighting how microstructure affects acoustic performance. We then analyze recent experimental findings on PU foam composites with ceramic microspheres, comparing their acoustic and mechanical properties, and dissecting the pros and cons of this approach. Key arguments and controversies in the field are addressed – for example, whether the primary benefit of microspheres is microstructural or related to the introduction of local resonant mass effects. Finally, we consider the implications and potential applications of these materials in automotive NVH control, including any practical challenges for implementation.

II. Porous Ceramic Microspheres: Characteristics and Roles in Composites

Porous ceramic microspheres are typically small spherical particles composed of ceramic material with either a hollow core or a network of internal pores. Unlike solid mineral fillers, these microspheres have much lower effective density and a high surface area-to-volume ratio. Fly-ash cenospheres are a common example – these are hollow aluminosilicate spheres formed as a byproduct of coal combustion, usually 50 – 300 μm in size and with densities around 0.4 – 0.8 g/cm³ (versus ~ 2.5 g/cm³ for solid silica) [14]. They consist of silica-alumina ceramic shells enclosing gas-filled interiors,

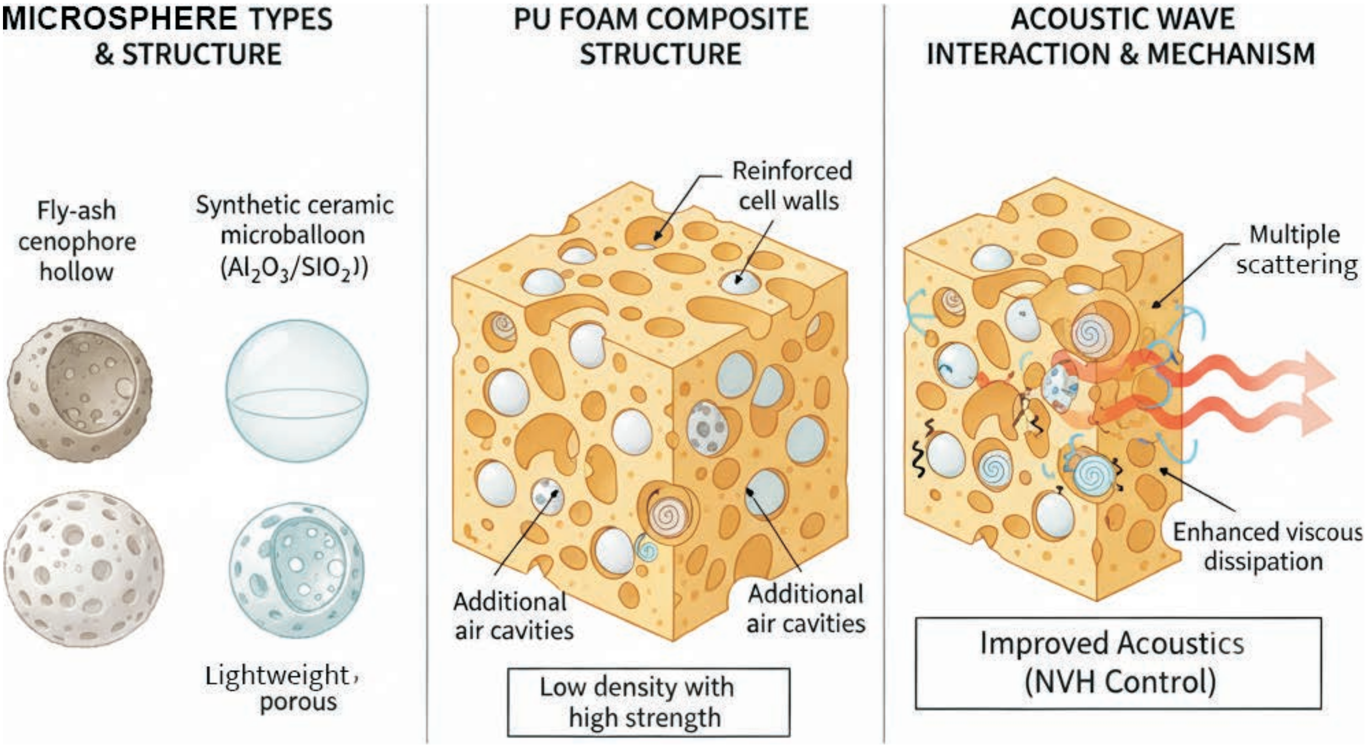

Fig. 1: Schematic illustration of porous ceramic microspheres embedded in PU foam for enhanced acoustic absorption.

making them lightweight yet fairly strong. Hollow glass microspheres (HGMs), often made of borosilicate glass, are another widely used type; they are manufactured to have thin-walled hollow structures, with typical diameters 10 – 100 μm and densities as low as ~ 0.1 – 0.3 g/cm³ [15]. More advanced variants include metal-coated or ceramic-coated hollow spheres, which can tailor properties like stiffness or electromagnetic behavior. There are also fully ceramic microspheres produced via spray-drying and sintering of ceramic powders [15]; these can be made from inexpensive raw materials and have controlled porosity. For example, Yan *et al.* [16] synthesized porous ceramic microspheres from waste coal gangue, achieving ~ 55 % porosity in spheres ~ 1 mm large.

The intrinsic properties of porous ceramic microspheres make them unique fillers for polymers. First, their low density means a significant volume fraction can be added to a foam without greatly increasing the composite weight – crucial for automotive uses where weight savings equate to better fuel efficiency or range. Second, they possess high compressive strength relative to their weight, so they can reinforce the foam structure. The ceramic shells can bear loads and restrain foam cell expansion, acting almost like an internal skeletal framework when the foam is under stress [17]. Third, these microspheres are thermally stable and often non-combustible, imparting improved flame resistance to the foam [18]. This addresses one drawback of organic foams, which are flammable; incorporating ceramic microspheres can help meet fire safety standards in engine compartments or vehicle interiors. Finally, their hollow/porous nature enables them to interact with sound waves in ways solid particles cannot. Each hollow microsphere in a polymer matrix can behave like a tiny resonant cavity or scatterer. Sound waves entering the foam may induce oscillations of the air inside the hollow spheres or cause the sphere's shell to vibrate, converting sound energy to thermal or mechanical energy dissipated in the matrix [19]. This effect is akin to embedding many local "Helmholtz resonators" or mass-spring-dampers inside the material. In fact, research in acoustic metamaterials highlights that embedding small resonant inclusions in a poroelastic matrix can greatly enhance low-frequency absorption beyond what the base porous material achieves alone [20]. Porous ceramic microspheres provide such inclusions in a random, broadband manner, without requiring the periodic structure that traditional metamaterials do.

When added to a PU foam formulation, ceramic microspheres tend to become distributed within the cell walls or strut junctions of the foam during its foaming process [21]. The presence of these rigid particles affects the foaming dynamics: the microspheres can act as nucleation sites for bubble formation, potentially increasing the number of cells and reducing average cell size [22]. They also consume some of the polymer mass that would otherwise form cell walls, which can effectively thin the cell walls if the microsphere content is small, or conversely, if microspheres accumulate, they can thicken regions of the cell wall where they cluster. The net result is often a foam with a modified microstructure – e.g. a more uniform cell size distribution and possibly a higher fraction of open cells. In other cases, the filler might block some cell windows and slightly reduce open porosity, as was observed when using surface-treated $CaCO_3$ particles in PU foam [21]: chemically treated particles led to lower open-cell content but surprisingly higher sound absorption, due to optimized flow resistivity. Clearly, the microstructural outcome depends on filler properties and processing conditions.

Table 1: Examples of porous microsphere fillers and their properties/effects.

Filler Type	Composition & Size	Density (g/cm³)	Notable Effects in Composites	Ref.
Fly-ash cenospheres	Alumino-silicate ceramic; 50 – 200 µm dia.	~ 0.6 (bulk)	Waste-derived, low-cost. Increase thermal stability; can improve acoustic insulation by creating additional porosity (cement + 40 % vol → 2 × NRC).	23
Hollow glass microspheres (HGMs)	Borosilicate glass; 10 – 100 µm dia.	0.1 – 0.4 (depends on grade)	Industrial additive for lightweight composites. In epoxy, adds air inclusions to tailor acoustic impedance. In fabrics, improved thermal and sound insulation when embedded in coatings.	24
Ceramic hollow microspheres (synthetic)	E.g. Mullite (Al_2O_3·SiO_2); 0.5 – 5 mm dia. (spray-dried)	0.7 – 1.4 (depending on porosity)	High-strength porous spheres. Used in porous ceramic foams; whisker-reinforced types achieve α_max > 0.8 (800 – 4 000 Hz) in ceramic foam. Can reinforce polymer foams (alumina spheres ↑ compression strength in PU).	18
Metal-ceramic hollow spheres	316L steel shell + alumina coating; ~ 1 – 3 mm	~ 1.8 (effective)	Heavy, rigid inclusions; introduce mass-spring effects. In PU, broaden absorption to lower frequencies; + 48 % compressive strength at 48 vol% loading. Used for sound insulation panels.	20

Table 1 summarizes typical properties of various porous microsphere fillers and their general effects when used in polymer composites.

In short, porous ceramic microspheres act as multifunctional foam additives. They are capable of refining the foam's pore structure and providing additional acoustic attenuation mechanisms, all while improving mechanical robustness and thermal resilience. The extent and nature of these effects, however, depend on the interplay between the filler and the foam's microstructure, which we explore in the next section. Understanding that interplay requires a closer look at how sound is absorbed in porous foams and what microstructural features are most important for acoustic performance.

III. Acoustic Absorption Mechanisms in PU Foams

Open-cell PU foams are classic porous absorbers – sound waves entering the foam cause air oscillation within the interconnected pores, and acoustic energy is dissipated primarily through viscous friction at the pore walls and thermal exchanges between the oscillating air and the solid matrix [25]. There are two fundamental damping mechanisms at work: (1) visco-inertial damping, where the drag forces as air flows through tiny channels convert sound energy to heat, and (2) thermal damping, where periodic compression and expansion of air in pores causes heat flow and energy loss. For typical flexible PU foams (with porosity > 90 % and cells of the order 100 – 500 µm), visco-inertial losses dominate in the audible frequency range, while the foam's solid frame (being soft) contributes little via structural vibration damping except at very low frequencies. Thus, the acoustic performance of a foam is highly sensitive to its non-acoustical parameters: porosity, tortuosity, flow resistivity, and pore size distribution [26]. These parameters are all governed by the foam's microstructure.

A crucial factor is the open porosity – the fraction of pore volume that is interconnected as opposed to closed off. Sound absorption requires air passage into the material; a fully closed-cell foam reflects most sound. Conversely, a fully open-cell foam allows easy airflow but if the flow encounters too little resistance, the frictional damping is small. Therefore, there is an optimal openness or flow resistance for absorbing sound. Park *et al.* [25] demonstrated this by intentionally manipulating cell openness in low-density PU foams (Fig. 2). They found that neither an entirely open nor entirely closed structure was ideal – instead, a foam where ~ 15 % of the cell windows remained closed achieved the highest absorption across a broad frequency band. This optimized partial openness increases the viscous drag on the air without completely sealing off pores. Similarly, Sung *et al.* [8] observed that foams with an open porosity of about 0.63 (63 %) yielded the best Noise Reduction Coefficient, whereas more open or more closed foams underperformed. In practice, standard acoustic foams often have 60 – 97 % open cells, and foam manufacturers sometimes perform reticulation to increase openness. The above studies indicate that a moderate level of flow resistance – achieved by a mix of open and partial

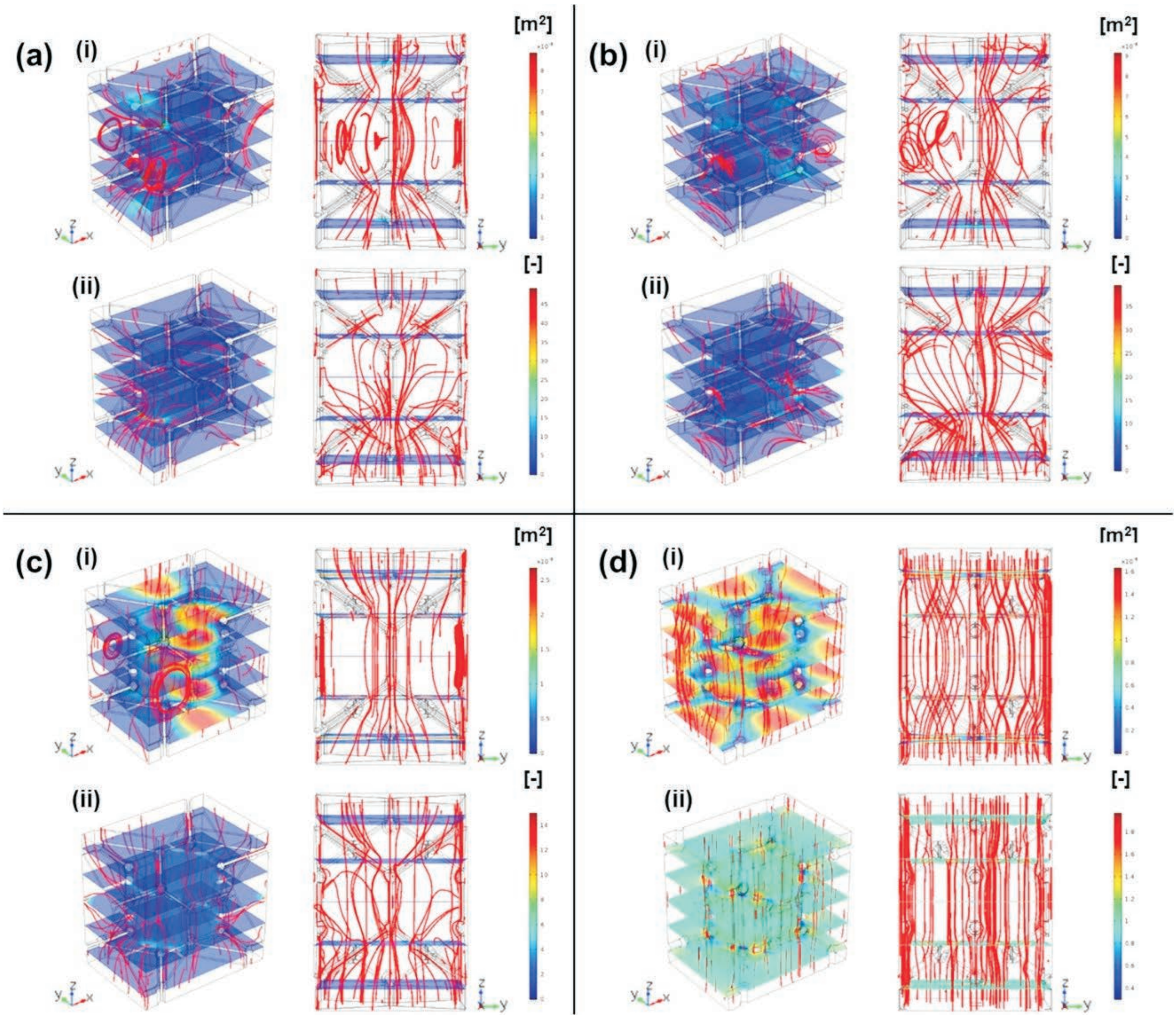

Fig. 2: Microscale numerical simulation results using PUCs with varied cell openness. The simulation results for (a) 15 %, (b) 25 %, (c) 50 %, and (d) 100 % openness PUC. (i) and (ii) show solutions for the viscous flow problem and inertial flow problem [25].

closed micro-windows – maximizes sound absorption in a given thickness.

Cell size and cell size distribution constitute another key microstructural aspect. The dimensions of the pores relative to the acoustic wavelength determine which frequencies are effectively absorbed. Smaller pores can increase high-frequency absorption because they create more frictional surface area for a given volume and higher flow resistivity [7]. However, if pores are too small or closed, low-frequency waves may not sufficiently penetrate or engage the material. Larger pores favor low-frequency absorption but if they are too large, the flow resistance drops and mid-frequency performance suffers [27]. Thus, a broad distribution of pore sizes can broaden the absorption spectrum, or a bimodal pore structure can combine low- and high-frequency dissipative effects. The work of Lin *et al.* [2] vividly illustrated how altering cell size impacts absorption: in their study, adding hollow microspheres led to a decrease in average cell size from ~500 µm (unfilled foam) to ~350 µm at high filler loading, and concurrently the high-frequency (2 – 4 kHz) absorption improved significantly. **Fig. 3** shows an example of how cell size distribution narrows and shifts to smaller diameters as more filler is added, indicating more numerous, finer cells in filled foam.

Besides average cell size, the cell size distribution also matters. A highly non-uniform foam might exhibit multiple absorption peaks tuned to different frequencies, but it could also mean that some regions of the foam provide little resistance while others provide too much. A moderate uniformity often yields more predictable, broadband performance. Lin *et al.* [2] found that an intermediate filler content (5 wt%) produced a very heterogeneous cell size distribution, which corresponded to irregular, “unstable” absorption in the low-frequency range. Higher filler contents eliminated those oversized cells, which not only improved mechanical strength but also made the absorption coefficient curves smoother and more monotonic with frequency[28]. This suggests that controlling cell size consistency is as important as controlling the mean size.

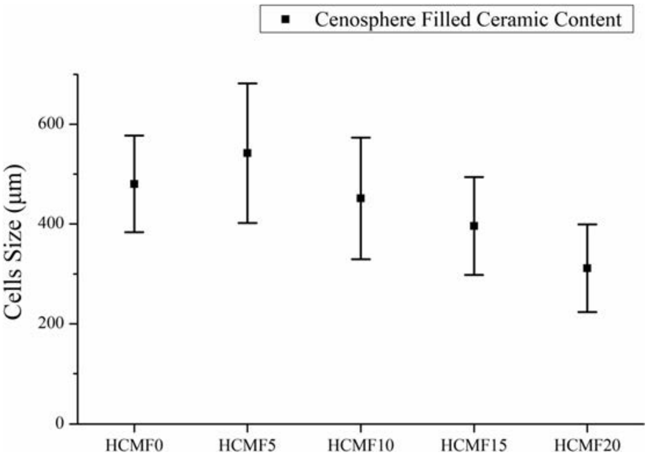

Fig. 3: Average cell size of flexible PU foam vs hollow ceramic microsphere content[2].

Another important parameter is the tortuosity of the pore channels – essentially how convoluted the pathways through the foam are. A more tortuous path means the sound-laden air has to travel a longer path in the material, encountering more friction. High tortuosity is usually associated with more complex cell connections and possibly the presence of micro-pores in the cell walls. Fillers that roughen or perforate cell walls can increase tortuosity and thereby absorption[29]. On the other hand, extremely straight, open channels let sound pass with less interaction. Effective acoustic foams often have a tortuous inner structure – either naturally from random cell arrangements or by design[30].

Frame elasticity and damping are more relevant for structure-borne noise or very low-frequency sound. A flexible foam can undergo frame vibration due to sound pressure; at low frequencies, this can absorb energy or, if the foam is too compliant, it can cause the foam to act almost like a spring and reduce absorption by coupling acoustic energy into mechanical motion without dissipation[25]. Generally, adding stiffness to the frame raises the frequency at which frame motion becomes significant. In lightweight automotive sound packages, one usually combines a porous absorber with a stiff facing or heavy layer if low-frequency noise must be attenuated. That said, the internal damping of the polymer and any energy dissipation in bending of cell membranes can contribute to absorption at mid-low frequencies. For instance, some studies have intentionally added viscoelastic particles or fibers to increase the loss factor of the foam frame and observed improved sound absorption especially around the foam's resonance frequencies[31]. Sujon *et al.*[32] reviewed polymer composites and noted that inclusions which enhance the interfacial friction or create constrained layer damping within the material can significantly increase acoustic energy dissipation in the 50 – 500 Hz range. In PU foams, this might translate to strategies like adding rubber particles or using phase-separated bicontinuous structures to get some frame-damping effect in addition to the usual air damping.

To summarize, the acoustic absorption of PU foams depends on a delicate balance of microstructural features: open vs closed porosity, pore size (and distribution), cell connectivity/tortuosity, and frame viscoelasticity. Table 2 highlights how some of these parameters affect absorption, with examples from literature.

Table 2: Influence of foam microstructure on acoustic absorption performance.

Microstructural Factor	Tendency and Acoustic Effect	Example Findings (Literature)
Open-cell fraction	Needs to be high enough to admit sound, but not 100 %. Optimal when foam has mixed open/closed windows to provide flow resistance.	Park *et al.*[25]: ~ 85 % open gave best absorption (15 % closed). Sung *et al.*: NRC peaked at ~ 63 % open porosity[8]. Fully open reticulated foam showed lower mid-frequency absorption than partially open foam of same density.
Pore size (mean)	Smaller pores → higher surface area → better high-frequency absorption; larger pores → favor low-frequency penetration. Need compromise or gradation.	Lin *et al.*[2]: reducing mean cell size from ~ 500 μm to ~ 350 μm increased absorption coefficients at 2 – 4 kHz by ~ 0.05 – 0.1 (dimensionless). Conversely, foams with very large cells (> 1 mm) lost absorption above 1 kHz[5].
Pore size distribution	Broad distribution can broaden absorption band, but too broad can cause uneven performance (large pores create acoustic leaks). A narrower, uniform distribution yields predictable, smooth absorption curve.	Lin *et al.*[2]: 5% filler foam had bimodal cell sizes (some very large, some small) → irregular low-frequency absorption. With 15 – 20 % filler, cell sizes uniform and absorption curve smoothed, with no sudden dips.

Microstructural Factor	Tendency and Acoustic Effect	Example Findings (Literature)
Tortuosity of pathways	High tortuosity (more convoluted paths) ↑ absorption by lengthening air path and increasing friction. Low tortuosity (straight pores) ↓ absorption (easy flow).	No direct numeric example in PU foam literature, but analogous to fibrous absorbers: adding bends or curvature in flow path increases effective path length and absorption. Foam example: impregnating foam with grapheme oxide increased tortuosity and improved absorption in a study by Yadav *et al.* [33].
Frame modulus & damping	Stiffer frame shifts any frame resonance to higher freq (often beyond interest range). Slight frame damping (loss factor) can improve absorption near resonance. Too stiff may reduce low-freq absorption by reflecting sound.	Baek *et al.* [31]: adding elastic silicone particles increased damping and friction, yielding higher absorption especially 500 – 1 000 Hz. Cork-filled rigid foam had high loss modulus, giving outstanding vibration damping (useful for structure-born noise). However, very high stiffness inclusions (metal) can cause impedance mismatch at boundaries, reflecting sound if not graded.

From the above, it is evident that the microstructure-acoustic property relationship in foams is complex. The ideal foam for sound absorption is one that lets sound in and then vigorously “rubs” and “works” on the air oscillations through a maze of tiny passages while perhaps also internally damping via frame motion. This ideal scenario is difficult to achieve with a pure polymer foam because some of these traits are mutually opposing. Microstructural refinement primarily governs the macroscopic acoustic properties described by the equivalent fluid models, such as the Johnson-Champoux-Allard (JCA) framework. In this model, sound absorption efficiency is quantitatively dictated by non-acoustic parameters like the static flow resistivity tortuosity, and characteristic viscous and thermal lengths. When lightweight microspheres nucleate finer cells and increase interfacial surface area. In contrast, the local resonance/inertia mechanism is dominant when the mechanical impedance of the inclusion significantly alters the effctive dynamic properties of the composite, an effect typically modeled using Mass-Spring-Damper (MSD) oscillators or specialized metamaterial formulations [6]. This mechanism is most pronounced when heavier or larger inclusions are used. Here, the characteristic resonance frequency is quantitatively related to the inclusion‘s effective mass, and the matrix stiffens. By manipulating the filler‘s size and density, researchers can deliberately shift the absorption band toward lower frequencies (e.g., 0.5 – 1 kHz), a region inaccessible with simple microstructural tuning. Therefore, maximum absorption gains achieved by modulating JCA parameters signify microstructural dominance, while clear shifts in the absorption peak due to filler mass/size indicate local resonance dominance.

IV. Enhancing PU Foam Absorption with Porous Ceramic Microspheres: Findings and Discussions

Research efforts over the past decade have increasingly shown that filling PU foams with porous ceramic microspheres can substantially improve their sound absorption performance, often alongside gains in mechanical strength. However, the extent of improvement and the mechanisms involved can vary, and there are nuanced pros and cons reported by different studies. We now review key findings, organize them by the type of filler or effect, and critically analyze the core arguments and controversies.

(1) Acoustic performance improvements

Multiple studies have demonstrated notable enhancements, especially at mid-to-high frequencies, and in some cases even at low frequencies by extending the absorption range. Lin *et al.* [2] reported that incorporating hollow ceramic microspheres (HCM) into flexible PU foam significantly boosted the high-frequency end of the absorption spectrum. In their impedance tube tests (125 – 4 000 Hz range), the baseline foam had a maximum absorption coefficient around ~ 0.30 – 0.35 at 3 500 Hz. With 15 – 20 % microspheres, the absorption at 3 500 Hz climbed to > 0.45 – roughly a 30 – 50 % increase in absorption coefficient in that high frequency band. Fig. 4 illustrates this trend: at frequencies above ~ 1 500 Hz, higher filler contents yield higher absorption, with HCMF20 (20 % filler) showing the best performance at 2 – 4 kHz. This improvement was attributed to the microspheres’ effect of creating smaller, more numerous cells and adding additional air-solid interfaces, which together increase the viscous and thermal damping of high-frequency sound waves. The absorption coefficient of the composite material reached a maximum of 0.85 at 3.5 kHz, with a sample thickness of 18 mm and an airflow resistivity of 2.5 kPa·s/m^2.

One might assume adding stiff particles would hurt low-frequency absorption, but the findings are more nuanced. In Lin *et al.*’s work [2], at low frequencies (125 – 500 Hz) the highest filler samples were not the best – interestingly, the foam with 5 – 10 % filler had higher absorption in that sub-1 kHz range than the 15 – 20 % filler foam. All filled foams still matched or exceeded the baseline’s low-frequency absorption, but there was a peak performance at moderate filler content for low-frequency behavior. The authors explained that a small amount of HCM disrupted the cell structure enough to improve low-frequency dissipation without yet making the frame too rigid. On the other hand, very high filler contents, while great for high frequency, slightly reduced the absorption below 1 kHz relative to the 5 % case – likely because the foam became more homogeneous and stiffer, thus reducing frame-related damping

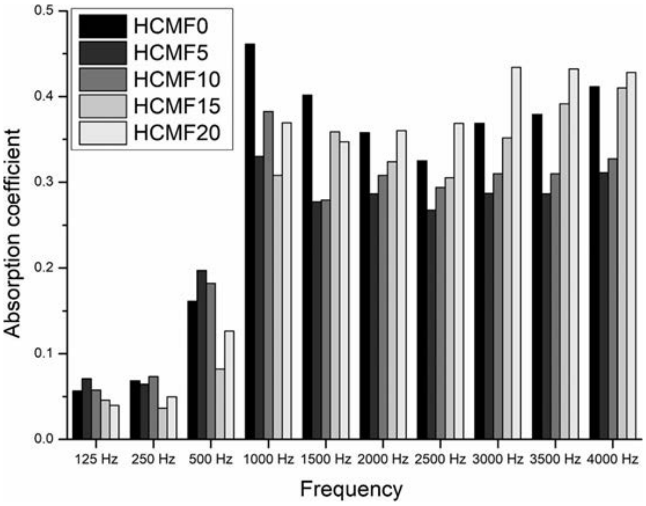

Fig. 4: Sound absorption coefficient vs frequency for PU foams with varying hollow ceramic microsphere content (0, 5, 10, 15, 20 wt%) [2].

at low frequency. This trade-off suggests an optimal filler fraction when targeting broadband absorption, a point of debate we will revisit. It is worth noting that another study by Jiang *et al.* [20] found that adding larger, heavier hollow spheres to a PU matrix shifted absorption towards lower frequencies. In that case, the composite acted more like a syntactic foam, and the heavy inclusions introduced a mass-spring resonance that improved sound transmission loss (STL) and absorption in the low kHz range compared to neat PU. The double-layer steel/alumina spheres were particularly effective, broadening the absorption band on both low and high ends. This finding underscores that filler size/density can drastically alter which frequencies are most affected – heavier, larger microspheres contribute to low-frequency absorption via local resonance and inertia effects, while small lightweight microspheres mainly enhance high-frequency absorption via microstructural refinement. This fundamental mechanistic duality is visually clarified in Fig. 5.

A common single-number metric for absorption is NRC (the average absorption at 250, 500, 1 000, 2 000 Hz). Sung *et al.* [8] measured NRC for PU foams with $Mg(OH)_2$ filler. The unfilled foam had an NRC around 0.25; the optimal filler-loaded foam (1 wt% $Mg(OH)_2$) achieved NRC ~ 0.43 (~ 70 % increase). Notably, if filler content was increased beyond 1 %, NRC started to drop, indicating too much filler began to degrade the pore structure openness. This again highlights the importance of finding a "sweet spot" in filler loading. Table 3 compiles results from several studies to give a quantitative sense of acoustic improvements achieved.

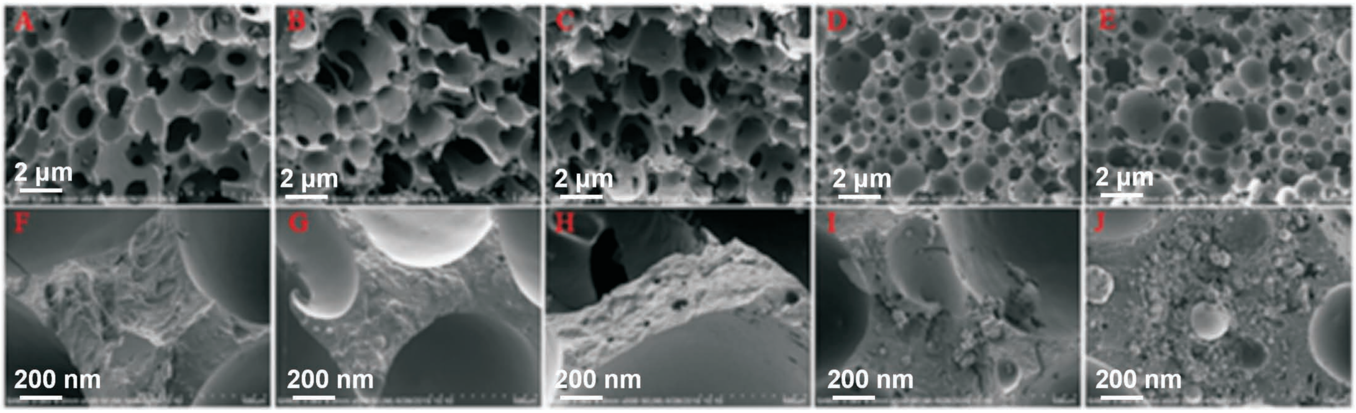

Fig. 5: (A) Visco-inertial loss via microstructural refinement (high-frequency). (B) localized mass-spring resonance (low-frequency extension).

Table 3: Acoustic absorption improvements with various fillers in PU foams.

Study (Year)	Filler Type & Loading	Notable Acoustic Results (vs unfilled foam)
Lin *et al.* 2022 [2]	HCM (fly-ash based), 0 – 20 wt%	+ 0.10 (absolute) increase in absorption coefficient at 3 500 Hz with 15 – 20 % filler; absorption at 2 000 – 4 000 Hz improved for higher filler, while 125 – 1 000 Hz range best at 5 – 10 % filler (all filled cases ≥ baseline). Overall, more filler = broader high-frequency absorption.
Sung *et al.* 2016 [3]	$Mg(OH)_2$ nanoparticles, 0 – 5 wt%	Optimal ~ 1 wt% filler gave NRC ≈ 0.42 (baseline ~ 0.25, + 68 %). Filler created partially open cells (63 % open, ideal) and enhanced damping. Excess filler (> 2 %) overdid cell opening and lowered NRC to ~ 0.3. Strong mid-frequency (500 – 1 000 Hz) absorption gains at 1 %.

Study (Year)	Filler Type & Loading	Notable Acoustic Results (vs unfilled foam)
Choe *et al.* 2020 [21]	$CaCO_3$ microspheres (~ 50 µm), 10 phr (parts per hundred polyol) treated vs untreated	Chemically treated $CaCO_3$-filled foam had higher absorption coefficients across 500 – 2 000 Hz than both unfilled and untreated-filled foam. E.g., α (1 000 Hz) increased from ~ 0.25 (unfilled) to ~ 0.35 (treated filler). Untreated filler gave little change or slight decline due to poorer dispersion.
Mohammadi *et al.* 2021 [30]	Rock wool fiber (avg 60 µm dia, several mm long), 0 – 15 wt%	Adding mineral fiber improved absorption at mid-high frequencies (1 000 – 2 000 Hz) significantly: e.g., α(1 250 Hz) from ~ 0.30 to ~ 0.50 at 10 % fiber. Low-frequency (< 500 Hz) absorption remained low for all, as expected for thin foam, but fiber presence slightly helped 250 Hz. Optimal ~ 10 % fiber; 15 % gave diminishing returns due to fiber agglomeration.
Jiang *et al.* 2020 [20]	Hollow spheres: (a) 316L stainless steel, (b) steel + Al_2O_3 coating; 30 – 50 vol%	With hollow spheres, sound transmission loss (STL) improved by ~ 5 – 10 dB in 500 – 1 500 Hz range vs solid-filled or neat PU. Absorption coefficient in 500 – 1 000 Hz also increased (notably for coated spheres). The absorption spectrum shifted to lower frequencies – absorption peak of composite at ~ 800 Hz vs ~ 1 200 Hz in neat foam. Compressive stiffness doubled with spheres.

From Table 3, we see consistently that moderate filler additions can yield sizable acoustic benefits. The specific frequency range of improvement depends on filler characteristics: nano/micro particles tend to boost mid-high frequency absorption by micro-scale effects on porosity, whereas large or heavy inclusions can introduce low-frequency resonance absorption. Nearly all studies emphasize an optimal filler content beyond which acoustic gains diminish. This optimal point often aligns with where the foam's microstructure is best "balanced" between open porosity and structural integrity.

(2) *Microstructural and mechanical effects*

In tandem with acoustic measurements, studies have examined how microsphere fillers alter foam morphology and mechanical properties. Understanding these changes is crucial, as they often explain the acoustic results and also determine the foam's suitability for automotive use (where mechanical durability matters).

One of the clearest benefits of adding ceramic microspheres is a more stable, intact cell structure. Lin *et al.* [2] observed that with HCM filler, the foam's cells were more spherical and less likely to collapse or coalesce during foaming. SEM images showed that at 20 % filler, cell walls were reinforced by embedded microspheres, preventing the formation of excessively large voids. Fig. 6 provides SEM views comparing an unfilled foam vs a high-filled foam. The filled foam clearly exhibits a finer, more uniformly distributed pore structure, with many microspheres visible as white circular features adhered to the cell walls.

Enhanced stiffness could be a double-edged sword for absorbing impact or vibration. On one hand, a stiffer, stronger foam can endure impacts without collapsing; on the other, it may transmit more force if it doesn't deform enough. Experiments on *impact attenuation* revealed a non-monotonic effect of filler [2]. The peak impact force transmitted through the foam initially dropped when adding filler (meaning better shock absorption up to 5 % filler), but beyond 5 – 10 % filler it increased again, indicating the foam became too stiff to absorb energy effectively. Fig. 7 illustrates this: the impact force was lowest for HCMF15 and HCMF20 – around 1 950 N, compared to 2 579 N for unfilled – but at 5 % filler it was actually highest (~ 3 018 N). This somewhat confusing result was interpreted as follows: small filler addition improved the foam's ability to damp impact by increasing its internal friction, whereas too much filler made the foam matrix so rigid that it rebounded more [2]. In fact, the optimal impact performance was at 5 % filler, which transmitted the least force (i.e. best cushioning) – contradicting a naive expectation that more filler always improves impact resistance. The authors noted that high filler content can lead to agglomeration that creates stress concentrations. Additionally, polymer chain mobility is crucial for viscoelastic damping [34]; too much inorganic content can hinder the polymer's molecular movement and reduce viscoelastic energy dissipation. This is a classic example of how a filler can improve one aspect while compromising another if over-used. Nonetheless, all filler levels studied still had better impact resistance than the unfilled foam in terms of absorbing shock. For automotive NVH, this implies microsphere-filled foams could serve dual purposes – acoustic absorption and vibration damping – if filler levels are tuned properly. A filler content around a few weight percent might maximize vibration damping [35], whereas higher content maximizes stiffness-related properties. Designers might choose a mid-level filler to balance both.

Direct measurements of airflow resistivity or open porosity with filler are not always reported, but we glean some info. Choe *et al.* [21] measured open porosity for their $CaCO_3$-filled foams. They found that untreated $CaCO_3$ filler slightly increased open porosity, whereas oleicacid-treated $CaCO_3$ led to a decrease in open porosity compared to unfilled foam. The chemically treated filler had better adhesion to the polymer, thus it might have kept some cell windows from opening during expansion, or thickened cell walls and thereby closed tiny pores. Interestingly, the foam with lower open porosity had higher sound absorption – reinforcing that maximum absorption doesn't always correspond to maximum open porosity, but rather an optimal value. The treated filler also gave higher compression strength, indicating a positive correlation between the foam's structural integrity and its acoustic performance in that case. We can infer that the treated filler foam had higher flow resistivity, which improved acoustic absorption by not letting air flow too freely. This aligns with the earlier discussion on optimal flow resistance.

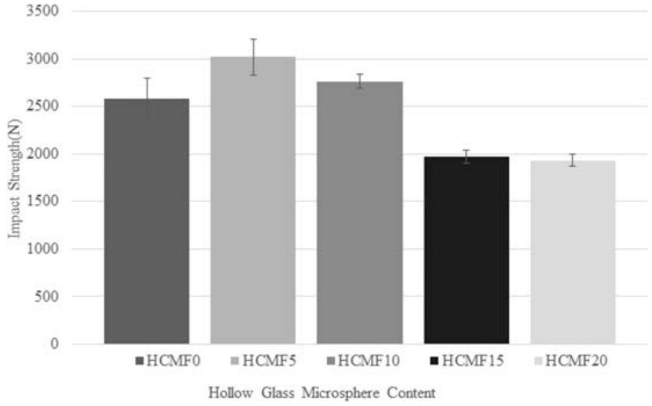

Fig. 6: SEM images of flexible PU foam without filler (A, B, top) vs with 20 wt% HCM (HCMF20; F, J, bottom).

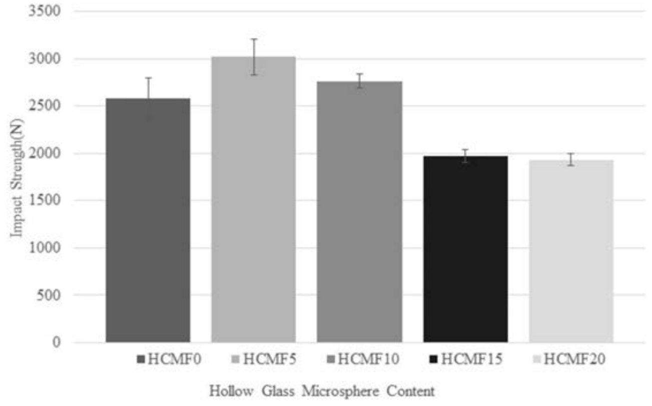

Fig. 7: Impact test results (drop-weight transmitted force) for foams with 0 – 20 % microspheres [2].

A practical challenge noted is ensuring uniform filler dispersion. At higher loadings, microspheres can clump together due to their surface chemistry or simply high local concentration [36]. Agglomerates in the foam can act like localized "defects" – regions of very high solid content that might behave almost like embedded gravel, contributing little to absorption and potentially initiating mechanical failure under strain. They also can cause non-uniform cell structures around them. Techniques to mitigate this include surface functionalization of microspheres, or using high-shear mixing and anti-settling agents during foam preparation. Lin *et al.* [2] mention pre-mixing the HCM in polyol for 10 min to help distribute it before adding isocyanate for foaming. Such steps are important for reproducibility and maximizing the benefits of the filler. Scholars opposing the filler approach often point out that if the filler is not well-dispersed, you might just as well have a foam with big chunks of inert material that do nothing or even reduce absorption by taking up volume. Thus, successful implementation hinges on good dispersion.

Adding any filler will increase the foam's bulk density to some extent (though with hollow microspheres, this penalty is small). For instance, if a foam had density 0.03 g/cm³ and one adds 20 wt% HCM (density ~ 0.7 g/cm³), the new density would be roughly $0.03(1-0.2) + 0.70.2 = 0.0324 + 0.14 = \sim 0.172\ g/cm^3$. But in reality, the volume of foam increases slightly due to filler occupying space foaming can't, so foam polymer density fraction might drop. For automotive NVH, a moderate density increase might be acceptable if the acoustic performance per weight is still improved. HCM strike a good balance by being far lighter than solid fillers – e.g. compare adding 20 % hollow glass microballoons vs 20 % calcium carbonate: the latter would add much more mass. Thus, the choice of porous microspheres is deliberate to minimize weight impact. Nonetheless, one should weigh the acoustic gain against any weight or volume change. If a certain absorption can be achieved by simply using a thicker foam of the same weight, that might be preferable over adding filler; but often space is constrained in vehicles, so a thinner composite foam with filler achieving equal absorption is a win.

The above pros and cons reveal a key theme: balance and optimization. There is a consensus that some amount of filler can improve foam performance, but too much can introduce new problems. The "core argument" among researchers centers on *how* exactly the fillers improve absorption and where the point of diminishing returns lies. Some argue the effect is mostly through microstructure. Others emphasize the *physical acoustic* role of the filler – i.e., the hollow spheres themselves acting as resonators and damping units – pointing to results like Jiang's where heavy spheres clearly added a resonant absorption, or Sung's suggestion that $Mg(OH)_2$ particles enhanced "damping motion" of the polymer [8]. In truth, both perspectives are valid and not mutually exclusive. For lightweight microspheres, the microstructural mechanism is probably dominant. For heavier or larger microspheres, their individual acoustic scattering and resonance can be significant. Tiny ones alter the microscale porosity finely but might not strongly interact with low-frequency waves; large ones can take on low-frequency resonant roles but might leave the high-frequency microstructure relatively unchanged. A hybrid approach could even be envisioned – combining different sizes to target multiple bands.

(3) Quantitative analysis of non-monotonic performance

The acoustic performance of porous ceramic microsphere (PCM)-filled polyurethane (PU) foams exhibits an inherently non-monotonic relationship with filler loading. Performance initially improves as concentration increases, reaches a specific frequency-dependent maximum, and subsequently declines as adverse physical phenomena – primarily structural stiffening, agglomeration, and flow restriction – begin to dominate. Understanding the complex trade-offs that define the location of the “optimal filler fraction” is crucial for rational, model-guided material design in automotive Noise, Vibration, and Harshness (NVH) control. Modeling approaches based on poroelastic theories, such as the Johnson-Champoux-Allard (JCA) model, are frequently used to predict sound absorption coefficients (α) by linking key parameters (flow resistivity, tortuosity, and porosity) to filler content.

Optimized sound absorption in PCM-filled foams relies on striking a delicate balance between two primary, and often conflicting, microstructural outcomes: (1) achieving maximized internal surface area for viscous losses through microstructural refinement, and (2) maintaining an optimal fluid flow resistivity (σ) to ensure adequate acoustic wave penetration while maximizing frictional drag. Different filler concentration regimes favor distinct outcomes.

At low to moderate filler concentrations, typically ranging from 5 wt% to 10 wt% of hollow ceramic microspheres (HCMs), the primary acoustic benefit is realized through the modification of the polyurethane foaming kinetics. The microspheres act as nucleation sites, which promotes finer and more uniform cell structures compared to the unfilled base foam. This loading regime is critical for establishing the optimal flow resistivity required for efficient sound absorption across the mid-frequency (MF) and low-frequency (LF) bands (125 Hz to 1 500 Hz). Effective acoustic absorption requires σ to be high enough to generate significant viscous friction as air oscillates through the interconnected pores, but concurrently low enough to permit sufficient wave penetration depth into the bulk of the material. Experimental results from the literature demonstrate that maximum absorption efficiency often occurs when the open porosity is not 100 %, but rather at an optimal partial openness; for example, an optimal open porosity of 63 % yielded the best Noise Reduction Coefficient (NRC) in $Mg(OH)_2$-filled foams. LML achieves this balance: the dispersed microspheres slightly thicken the cell struts or partially obstruct cell windows, preventing air from flowing too freely.

Furthermore, LML preserves sufficient polymer matrix viscoelasticity, allowing the solid frame to contribute to damping, particularly below 1 kHz. Excessive stiffening, which is characteristic of higher loadings, tends to increase surface reflection and reduce frame-related dissipation. The observation that the minimum transmitted impact force (indicating optimal dynamic energy absorption/cushioning) occurred at 5 wt% HCM confirms that this regime strikes the best practical compromise between acoustic performance, mechanical integrity, and dynamic damping characteristics required for balanced NVH mitigation. The NRC for flexible PU foams often peaks in this regime; for instance, modeled data based on HCM research shows that the highest NRC is achieved near 5 wt% loading.

As filler content is increased further, the principal acoustic gains shift dramatically toward the high-frequency (HF) range (2 kHz to 4 kHz). This shift is directly correlated with the maximized refinement of the cellular structure. High loading maximizes the number of cell nucleation sites, consistently leading to the lowest average pore size observed in the composite – for instance, reducing the mean cell diameter from approximately 500 μm down to 350 μm at 20 wt% loading. Since high-frequency sound waves rely predominantly on viscous friction losses generated at the air-solid interface, maximizing filler content effectively maximizes the internal surface area and cell density. This maximizes the viscous drag coefficient for HF oscillations, explaining why the highest absorption coefficients above 1.5 kHz are consistently achieved at the highest tested loadings (15 wt% to 20 wt%). Specific gains reported include absorption increases of approximately 30 % to 50 % at 3.5 kHz, with the maximum α 3 500 Hz typically occurring around 20 wt%.

Beyond the identified high-frequency optimum, acoustic performance inevitably deteriorates across all bands due to compounding physical constraints. The cumulative effect of numerous rigid ceramic inclusions leads to a significant stiffening of the polymer matrix. This significantly increases the material’s surface acoustic impedance, causing greater sound reflection at the foam/air interface and particularly degrading performance in the sub-kilohertz range. Furthermore, very high filler concentrations increase the likelihood of microsphere agglomeration, as noted in studies on mineral fibers and other fillers. These agglomerates act as localized structural defects, blocking critical interconnected pores and causing non-uniform flow resistivity, which reduces overall absorption efficiency. While LML achieves optimal σ, excessive content pushes the flow resistivity beyond the functional limit, effectively sealing off large sections of the porous network and preventing acoustic energy penetration into the material‘s bulk.

V. Automotive NVH Applications and Considerations

The ultimate value of enhancing PU foams with porous ceramic microspheres lies in applying these advanced materials to real-world noise control in vehicles. Automotive NVH engineering spans a frequency range from below 20 Hz up to several kHz [37]. Traditional sound packages in cars use a combination of absorbers for mid-high frequencies and barriers or resonators for low frequencies [38]. A foam that could offer improved absorption across a wider frequency range or replace multi-layer solutions with a single material would be highly attractive for simplifying manufacturing and potentially reducing weight or thickness.

Likely in many of the same places as current acoustic foams, but with better performance: headliner insulations, roof trim, door cavity fillers, pillar stuffers, dash insulator pads, engine covers, and even under-carpet decoupling foams. Each area has its own dominant noise spectrum [39,40]. For instance, the engine bay and firewall region face a lot of broadband noise, including low frequencies. Here, a microsphere-filled foam could be used as part of an engine cover or hoodliner. Covestro (a materials supplier) notes that their Bayfit® PU foams are used for engine covers to provide both insulation and absorption in the engine bay. If such foams were modified with ceramic microspheres, they could likely handle the high temperatures and possibly provide better low-frequency absorption where engine mount or road boom noise comes through. The flame resistance of ceramic-filled foam is a big plus for engine applications – conventional acoustic foam requires additional fireproof facings or must be formulated with heavy flame retardants, whereas adding inert ceramic naturally helps it resist burning.

Inside the cabin, headliner and pillar areas mainly combat wind and road hiss. A thin foam layer is often used on the roof under the headliner fabric. Using a microsphere foam here could allow either a thinner layer for the same absorption or markedly better absorption of high-pitched wind noise without increasing thickness. Particularly for EVs, which lack engine noise, improving high-frequency absorption is key to perceived silence. The study by Wilk-Jakubowski *et al.* [41] reviewing new sound insulating materials emphasizes the push for advanced lightweight absorbers for EVs and notes the trend of using composite materials and hybrid structures to achieve broad spectrum noise control. The technology of microsphere-filled foam fits well into this trend, offering a hybrid material (polymer + ceramic) with multifunctional advantages.

For floor and carpet regions, the main issue is low-frequency road noise and tire cavity noise [42]. Standard practice is to use a heavy mass layer to block these and a foam as a decoupler [43]. While a foam – even with fillers – cannot replace the mass layer for true low-frequency blocking, it can contribute to absorption in that range more than a plain foam would [44]. Jiang's work suggests that if required, a heavier syntactic foam could be formulated to serve as a combined absorber/blocker for moderate low frequencies [20]. However, in most cases, the microsphere foam might be used as a decoupling layer that would also add absorption, allowing perhaps a lighter mass layer than before, or none for slightly higher frequencies. For example, the wheel well liners could incorporate such foam to absorb tire noise where space for a thick liner is limited.

Another potential application is in EV battery packs: These often have cooling foam pads or structural foam fills that also need to damp noise [45]. A thermally conductive foam with ceramic content could double as a heat spreader and a noise absorber around the battery enclosure [46].

From an NVH design perspective, a material like HCM-filled PU foam can reduce the reliance on purely passive heavy solutions by attacking noise at the source via absorption. In practice, an NVH engineer might use a microsphere foam to line cavities and reduce reverberation [47]. The double benefit of improved acoustic and mechanical performance means less risk of foam degradation over life. Foams in cars can get rattled, compressed, and aged; the ceramic reinforcement can help them keep their shape and adhesion. For instance, door cavity fillers (small foam blocks in doors to prevent drum effect) sometimes crumble or settle – a sturdier filler-enhanced foam would avoid that, maintaining noise attenuation over time.

It appears to be on the cusp. Patent literature and supplier brochures are beginning to mention "hybrid foam" or "nano-composite foam" for acoustic uses. A product like Hy-Brid® coating (by Acry-Tech) uses ceramic microspheres in a paint-on damping coating, touted to reduce panel vibrations and airborne noise [48]. While that is not a foam, it shows industry acceptance of ceramic microspheres in automotive acoustic solutions. It is reasonable to expect that foam part manufacturers are experimenting with filling their PU foams with such microspheres to meet tighter noise regulations without adding weight.

Cost and production must be considered as well [49]. Adding fillers can slightly complicate foam formulation and add material cost [50]. For automotive, any new material must pass a battery of tests: temperature/humidity aging, vibration, compression set, flammability (FMVSS 302, etc.), and so on [51]. The evidence so far indicates microsphere-filled foams would generally improve performance in many of these tests. Moisture might be a consideration – ceramic particles won't absorb water, but they could possibly create wicking paths [52]. However, most microspheres are closed-shell and hydrophobic, so this will likely not be an issue.

By varying filler type and amount, the foam can be "tuned" [53]. This tunability is very valuable in NVH design where each vehicle model might need slightly different acoustic tuning [54]. For instance, a luxury sedan might employ a slightly higher filler content foam in the roof to achieve a very hushed high-frequency sound, whereas a small economy car might use a lower filler content just to stiffen the foam enough for modest gains (keeping cost and weight as priorities). The existence of an optimal filler content that maximizes absorption for a given thickness provides a new parameter for NVH optimization beyond just foam density and thickness.

One caution is that in some automotive applications, foam is also used for thermal insulation. In those cases, adding ceramic might increase thermal conductivity slightly, reducing insulation performance. However, tests like those performed by Pakdel *et al.* 24 on fabric with HGMs showed that while HGMs added acoustic and flame benefits, they did not drastically impair thermal insulation – in fact, they can even create an insulating air-bubble effect. For foams, the effect might be minimal unless filler loading is very high.

To connect back to NVH metrics: even a 1–2 dB reduction in noise or a shift in frequency that avoids a resonance can be the difference between meeting or failing a target. If microsphere foam can, for example, absorb a bit more of the 1 kHz windshield noise, it might reduce the need for thicker laminated glass. Or if it attenuates the 3–4 kHz range better, perhaps the sound of an electric motor's inverter whine (often ~ 8 kHz switching, which has harmonics in audible band) might be less noticeable [55].

VI. Conclusions

This review establishes that embedding porous ceramic microspheres into polyurethane foams is a practical pathway to lightweight, broadband acoustic absorption for automotive NVH. Two complementary mechanisms underpin the gains: microstructural tuning (finer, more uniform cells; moderated openness; increased tortuosity) that elevates viscous/thermal losses in the 2 – 4 kHz range, and local mass-inertia/resonant effects (with larger/denser spheres) that extend absorption toward 0.5 – 1 kHz – useful for road/structure-borne content. Performance is non-monotonic with loading; moderate filler fractions maximize broadband absorption and dynamic damping, whereas excessive contents stiffen the frame, encourage agglomeration, and can suppress sub-kilohertz response.

FACs add an important sustainability and cost dimension. Life-cycle assessments indicate that cenosphere-based materials can reduce embodied impacts versus conventional mineral fillers, while retaining mechanical integrity at low density; however, benefits depend on collection/beneficiation logistics and transport distances, which should be reflected in plant-specific LCAs during sourcing. At the same time, cenospheres are not monolithic commodities: their shell chemistry (SiO_2/Al_2O_3 ratio), wall thickness, and size distribution vary with coal type and combustion conditions, necessitating quality control windows (e.g., target bulk density ranges, crush strength, and narrow particle-size cuts) to ensure reproducible acoustic and mechanical properties in foams. Recovery/beneficiation (e.g., floatation, density banding, magnetic separation) mitigates variability and removes heavy fragments that could seed agglomeration or flow blockage.

Evidence from polymer composites and FAC-based plates corroborates the acoustic potential of cenosphere inclusions supporting their translation into PU foams for thin acoustic packages under tight packaging constraints typical of headliners, pillars, and wheel-well liners. Going forward, we recommend: (i) spec-driven procurement of FACs (density, crush strength, size), (ii) dispersion and surface-treatment protocols to prevent clustering, (iii) graded fillers (light + heavy spheres) to tailor spectra without mass penalties, and (iv) model-guided tuning (JCA-parameter inversion + impedance-tube screening) coupled to NVH-relevant durability (FMVSS-302, humidity/thermal aging). Framed this way, waste-derived cenospheres are not merely "green" fillers – they are value-adding acoustic design levers that can reduce reliance on heavy barriers and help meet emerging EV sound-quality targets with thinner, lighter, and more durable packages.

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