Recent Trends in Porous Sound-Absorbing Materials

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Sound-absorbing materials absorb most of the sound energy striking them, making them very useful for the control of noise. They are used in a variety of locations - close to sources of noise, in various paths, and sometimes close to receivers. Although all materials absorb some incident sound, the term "acoustical material" has been primarily applied to those materials that have been produced for the specific purpose of providing high values of absorption. The major uses of absorbing materials are almost invariably found to include the reduction of reverberant sound pressure levels and, consequently, the reduction of the reverberation time in enclosures, or rooms. A wide range of sound-absorbing materials exist. In the 1970s, public health concerns helped change the main constituents of sound-absorbing materials from asbestos-based materials to new synthetic fibers. Although, these new fibers are much safer for human health, more recently, issues related to global warming may increase the use of natural fibers instead of synthetic ones.

Noise and vibration are of concern with many mechanical systems, including industrial machines, home appliances, vehicles, and buildings.1-3 Noise and vibration can also be used as the source of signals for machinery diagnostics and health monitoring, although this topic will not be discussed here.^{4,5} Once noise and vibration sources have been identified, the noise and vibration of machinery can be reduced by the use of vibration isolation, barriers, sound-absorbing materials, machine enclosures or by cabin enclosures used to protect passengers in the case of aircraft or vehicles.^{6,7} Sound-absorbing materials should always be used in conjunction with barriers and inside enclosures to improve their effectiveness.⁸ Sound-absorbing materials have been used increasingly in the construction of aircraft, spacecraft and ships because of their low weight and effectiveness when used correctly. This trend is driven by demands for higher load capacity and reduced fuel consumption for cars, trucks and aerospace structures. The optimum design of vibro-acoustical systems can be achieved through a variety of methods including statistical energy analysis (SEA).⁹

In the last 40 to 50 years, the use and variety of available specialized sound-absorbing materials has increased greatly. This has been due mainly to both improve technology and public concern about noise in everyday life. Architects and acoustical engineers now have a wide choice of sound-absorbing materials that not only provide the desired acoustical properties, but also offer an extremely wide variety of colors, shapes, sizes, light reflectivity, fire ratings, and methods of attachment – to say nothing of the costs of purchase, installation, upkeep, etc.⁸

In the 1970s, a series of events related to public health concerns made makers of sound-absorbing materials change the main constituents of their products from asbestos-based materials to new synthetic fibers. These new fibers are much safer for human health. More recently, issues related to global warming caused by the emission of greenhouse gases into the atmosphere by industrial manufacture of materials may change the acoustical materials market. The production of synthetic materials contributes to the emission of carbon dioxide (mostly from power plants and transportation), methane, and nitrous oxide. Thus, the total set of greenhouse gas emissions caused directly and indirectly by material production affects its carbon footprint, which may become increasingly important in future world trade considerations. Moreover, the concept of "green" building materials is used in practice in several European countries. In addition, public awareness and concern about the negative effects of pollution has led consumers to favor environmentally friendly materials, less contaminating processes, and



Figure 1. Schematic cross-section of a porous solid material (adapted from Ref. 12).

recycled products. Therefore, it is important to increase research on acoustical materials based on renewable resources that can lead to viable alternatives to conventional materials for current and future applications.^{10,11}

In addition, recent advances in material science, chemistry, and nanotechnologies are producing significant improvements in the design, production, and performance of acoustical materials. These advances include the use of natural fibers, bio-based polymers, recycled and surplus materials, porous metals, new composites, and smart materials.

Porous Absorbing Materials

Sound-absorbing materials absorb most of the sound energy striking them and reflect very little. Therefore, sound-absorbing materials have been found to be very useful for the control of noise. They are used in a variety of locations: close to sources of noise (close to sources in electric motors, for example), in various paths (above barriers), and sometimes close to a receiver (inside earmuffs).

A wide range of sound-absorbing materials exist; they provide absorption properties dependent upon frequency, composition, thickness, surface finish, and method of mounting. However, materials that have a high value of sound absorption coefficient are usually porous.⁸

A porous absorbing material is a solid that contains cavities, channels or interstices so that sound waves are able to enter through them. It is possible to classify porous materials according to their availability to an external fluid such as air. Figure 1 shows a schematic cross-section of a porous solid material. Those pores that are totally isolated from their neighbors are called "closed" pores. They have an effect on some macroscopic properties of the material such as its bulk density, mechanical strength and thermal conductivity. However, closed pores are substantially less efficient than open pores in absorbing sound energy. On the other hand, "open" pores have a continuous channel of communication with the external surface of the body, and they have great influence on the absorption of sound. Open pores can also be "blind" (open only at one end) or "through" (open at two ends). A practical convention is used to make a distinction between porosity and roughness, which assumes that a rough surface is not porous unless it has irregularities that are deeper than they are wide.¹²

Porous absorbing materials can be classified as cellular, fibrous, or granular; this is based on their microscopic configurations. Porous materials are characterized by the fact that their surfaces allow



Figure 2. The three main types of porous absorbing materials.

sound waves to enter the materials through a multitude of small holes or openings. Materials made from open-celled polyurethane and foams are examples of cellular materials. Fibrous materials consist of a series of tunnel-like openings that are formed by interstices in material fibers. Fibrous materials include those made from natural or synthetic fibers such as glass and mineral fibers.¹³ In addition, a porous absorbing material can also be granular. Consolidated granular materials consist of relatively rigid, macroscopic bodies whose dimensions exceed those of the internal voids by many orders of magnitude (agglomerates). Unconsolidated materials consist of loosely packed assemblages of individual particles (aggregates). Granular absorbing materials include some kinds of asphalt, porous concrete, granular clays, sands, gravel, and soils.^{14,15} So the acoustical properties of granular materials are an important factor in controlling outdoor sound propagation.¹⁶

Figure 2 shows the three main types of porous sound absorbing materials, their typical microscopic arrangements and some of the physical models used to describe their absorbing mechanisms.

When a porous material is exposed to incident sound waves, the air molecules at the surface of the material and within the pores of the material are forced to vibrate and, in doing so, lose some of their original energy. This is because part of the energy of the air molecules is converted into heat due to thermal and viscous losses at the walls of the interior pores and tunnels within the material. At low frequencies, these changes are isothermal, while at high frequencies, they are adiabatic. In fibrous materials, much of the energy can also be absorbed by scattering from the fibers and by the vibration caused in the individual fibers. The fibers of the material rub together under the influence of the sound waves.^{8,17}

The sound absorption mechanism in bulk granular materials is quite similar to that in rigid porous materials where the solid structure can be regarded as ideally rigid and stationary. Then the sound absorption is produced by the viscosity of the air contained inside the interconnecting voids that separate the granules. At low and mid frequencies, the solid structure interacts with the bulk of the gas through an isothermal heat transfer process. In addition, scattering from the granules also influences the absorption of sound energy inside the material.

Various models have been proposed to interpret the acoustical behavior of porous absorbing materials. Such models generally aim to derive the characteristic propagation constant, $\Gamma_{a'}$, and the characteristic wave impedance, Z_a , of a plane wave in the absorbing material as functions of non-acoustical properties such as porosity, air flow resistance and tortuosity.

The porosity of a sample of porous material is defined as the ratio of the volume of air in the void space (V_a) in the sample to the total volume of the sample. The air flow resistance is the resistance experienced by the air when it passes through open pores in the material. The tortuosity or "shape factor," as it is sometimes known, is a measure of the shape of the air void passages (whether they are almost straight or twisted and winding and slowly or rapidly changing cross section area) and the effect this has on the material sound absorption properties.⁸

In general, the basic theoretical approach used to describe the sound absorption of a porous material assumes that the frame of the sound absorber is constrained. Several models (and further improvements) have been developed using this assumption.¹⁸⁻²⁰ Although the complete poro-elastic model developed by Biot considers the fact that the frame is not constrained (elastic-framed material),^{21,22} simplified models of sound propagation give accurate enough results in most practical cases. The theoretical details and model comparisons have been discussed by several authors.²³⁻²⁷

Porous Fibrous Materials

Most of the porous sound-absorbing materials commercially available are fibrous. Fibrous materials are composed of a set of continuous filaments that trap air between them. They are produced in rolls or in slabs with different thermal, acoustical, and mechanical properties. Fibers can be classified as natural or synthetic (artificial). Natural fibers can be vegetable (cotton, kenaf, hemp, flax, wood, etc.), animal (wool, fur felt) or mineral (asbestos). Synthetic fibers can be cellulose (bamboo fiber, for example), mineral (fiberglass, mineral wool, glass wool, graphite, ceramic, etc.), or polymer (polyester, polypropylene, Kevlar, etc.).

Synthetic fibrous materials made from minerals and polymers are used mostly for sound absorption and thermal isolation. However, since they are made from high-temperature extrusion and industrial processes based on synthetic chemicals, often from petrochemical sources, their carbon footprints are quite significant.

Recently, the use of natural fibers in manufacturing soundabsorbing materials has received much attention.²⁸⁻³¹ Natural fibers are essentially completely biodegradable and modern technical developments have made natural fiber processing more economical and environmentally friendly. These new methods may result in increased use of high-quality fiber at competitive prices for industrial purposes. The absorption properties of sound-absorbing materials made of these fibers can be similar to those made from minerals. These properties can be modified by pre-treatments such as drying, carbonizing, impregnation, and mineralization. In addition, natural fibers are also safer for human health compared with most mineral synthetic fibers, since they do not need precautions in handling.

An important microscopic parameter of a fiber is its diameter. The fiber diameter is directly related to the sound-absorbing characteristics of the material. Table 1 shows a comparison of the average fiber diameters of several types of industrial fibers measured using electronic microscopy techniques. In general, the diameter of natural fibers tends to be larger than the diameter of synthetic fibers obtained by extrusion. Figure 3 shows some scanning-electron-microscope images of samples of hemp, kenaf, cotton and polyester fibers. It is evident that natural fibers have more irregular shapes and variable diameters compared to synthetic fibers.^{32,33}

Hemp (*cannabis sativa*) is one of the most important natural fibers. Hemp crops require virtually no chemicals in their production, since they are naturally resistant to most pests. On the other hand, cotton accounts for approximately 50% of all pesticides and herbicides used in U.S. agriculture today. In addition, hemp produces significantly more fiber per square meter than cotton or flax and uses less water to grow. Hemp fiber is naturally antimicrobial and resistant to ultraviolet light, mold, mildew, and insects, which makes it of potential use in outdoor applications. The United States is one of the largest consumers of hemp fiber in the world, although its cultivation is illegal in the U.S.

To examine the use of hemp fibers in the manufacture of soundabsorbing materials, some studies have reported values of the sound absorption coefficient of hemp felt of different thicknesses. Figure



Figure 3. Scanning electron microscope images of samples of hemp, kenaf, cotton and polyester fibers. Courtesy of Dr. J. Alba (Polytechnic Univ. of Valencia).

4 shows the sound absorption coefficient measured in a reverberation chamber of a 40-mm-thick thermal insulation material made of 80-85% of hemp fibers.³⁴

Kenaf (*hibiscus cannabinus*) is a different plant that is cultivated in the U.S. and is related to cotton. Its fibers have been used to strengthen concrete and other composite materials for construction applications and for materials used in the automotive industry. Materials for thermal isolation and acoustic absorption made of a mix of natural kenaf fibers, polyester fibers for strengthening, and a natural fireproof product, are currently available commercially.³¹

Evidently sound absorbing materials made of natural fibers such as hemp and kenaf can be recycled easily, and their production involves a low carbon footprint and no CFC emissions, so that they can be classified as ecologically green building materials. Therefore, they provide an alternative to chemical building materials, polymers, and other artificial nonsustainable materials.

Advanced Metal, Ceramic and Gel Foams

Although polyurethane and melamine foams are probably the cellular porous sound-absorbing materials currently most in use, other types of foams have been designed for environments where

Table 1. Average fiber diameter for several industrial fibers.		
Origin	Fibrous Material	Fiber diameter, µm
Synthetic	Ceramic	2-6
	Mineral wool (rock wool, slag wool)	3-10
	Fiber glass (continuous filament)	6-13
	Glass wool	3-7
	Graphite	5-10
	Basalt	7-13
	Bamboo	14
	Polypropylene	5-25
	Polyester	3-15
	Kevlar	12
Natural	Cotton	8-33
	Kenaf	21
	Hemp	22
	Wood	16-38
	Flax	19
	Bagasse	20
	Jute	20



Figure 4. Measured sound absorption coefficient of a material made of hemp fibers.

heat or corrosion resistance is required.

Metal foams are relatively new materials that have proven to be appropriate in the manufacture of lightweight structures, biomedical implants, filters, heat exchangers, sound absorbers and mechanical damping devices.³⁵ Aluminum foams have traditionally been the most commonly used foams. However, new raw materials are being used now to manufacture other types of foams, such as nickel, steel, titanium, and copper.^{36,37} Metal foams exhibit high stiffness, low weight, fire resistance and low moisture absorption. Metal foams are usually expensive although they can be recycled.

Depending on the manufacturing method used, metal foams can be either mostly open celled or mostly closed celled. Open-celled metal foams can be manufactured using polyurethane foams as a matrix base.³⁸ The resulting metal foam has values of porosity between 75-95%. Evidently the vibration of the skeleton can be neglected when modeling the sound absorption properties of metal foams. Open-celled metal foams with cell sizes from 0.2-0.5 mm are commercially available for high-temperature applications.

Closed-celled metal foams have a large number of small closed pores (typical pore size is 1-8 mm) filled with air, and these materials are usually employed as impact absorbers and as cores in sandwich panels. They are commonly made by injecting a gas (air, nitrogen, argon, carbon dioxide or carbon monoxide) or adding a foaming agent (titanium hydride or calcium carbonate) into molten metal. The powder metallurgical process is another industrial method used to produce metal foams.³⁷

Closed-celled materials do not absorb sound well. So metal foams of this type can be made more absorptive by either rolling or drilling holes. When rolled, the faces of some cells break and form tiny sharp-edged cracks forming passageways; this results in sound absorption caused by viscous flow across the cracks, by thermoelastic damping and by the cells acting as Helmoltz resonators.³⁹ In general, rolled-metal foams absorb sound well for frequencies just between 1 to 5 kHz, although they are not as efficient sound absorbers as polyurethane and melamine foams. However, metal foams present some advantages when a self-supported absorber is required for high temperature applications and harsh conditions.⁴⁰ Of course, better sound absorption can be obtained by placing the metal foam at a suitable distance from a rigid wall.

Note that metal foams have great potential for shock and vibration control applications because:

- The damping capacity of metal foams is larger than that of solid metals by a factor as much as 10.
- Foamed panels have higher natural flexural vibration frequencies than solid sheets of the same mass per unit area.
- Metal foams have exceptional abilities to absorb sound energy at almost constant pressure.
- Metal foams have the ability to absorb impacts at a constant crushing load.³⁵

Recent studies on innovative materials made of honeycomb-like structures composed of many tiny tubes or channels have been reported.⁴¹ A prototype micro-channeled material composed of metallic nanotubes has been developed to reduce noise in aircraft, although their sound-absorbing performance is still under study.

Ceramic foams are also an excellent alternative for high-temperature applications. These foams can be made in a similar way to polyurethane foams with open cell walls forming reticulated channels through the foams. They are usually made of siliconbased elements. However, it is possible to find foams made of other ceramic core elements, such as zirconium, titanium, and boron. Ceramic foams have porosities from 80-90% and can be used at temperatures over 1,500° C. New ceramic foams made of aluminum oxide can have porosity values over 94%. Currently, ceramic foams are used extensively in aerospace and industrial applications such as rocket nozzle components, composite panels, heat shield elements, and acoustical liners in aircraft mufflers.⁴²

Aerogels are another form of microporous materials used in some complicated applications. Aerogels are also known as frozen smoke and have been claimed to be the best thermal insulators ever made, being 40 times better than common fiberglass insulation materials. Aerogels are created by removing the liquid content of a gel by a supercritical drying manufacturing process. An aerogel has a monolithic internal structure being made of a highly porous, extremely lightweight and translucent material in which most of its volume is filled with air. Several raw materials have been used to produce aerogels, but silica aerogels are the most common. Its structure is composed of small spherical silicon dioxide clusters from 3-4 nm in diameter that are linked to each other forming chains that in turn form a spatial grid with air-filled pores.⁴³ The typical average size of the pores is 30 to 40 nm. The typical porosity of an aerogel is greater that 75%, and its melting point is 1,200° C.

Unfortunately aerogels are still very expensive, and these materials have been used primarily in high-tech aerospace missions by NASA. However, recent research has been oriented toward their use in granular form as sound-absorbing materials, where their mechanical behavior is intermediate between that of a gel and that of a granular material. Experimental results of multilayer absorbing panels made of silica aerogels have been presented by some authors.⁴⁴ A different approach has been related to the production of composite aerogels with varying concentrations of silica and poly-dimethylsiloxane, which decrease the material's rigidity. The average size and density of the pores can be controlled during the manufacturing process. Such composite aerogels have pore sizes between 5-20 nm, and experimental results have shown that these materials exhibit better sound-absorbing properties than those of commercial fiberglass.⁴⁵ It is very probable that advances in material science will reduce the cost of producing aerogels, which could lead to their widespread use in building and automotive industries in the near future.

Although the production of metal foams, ceramic foams, and aerogels can contribute to greenhouse gas emissions, their practical use in transportation will help in reducing other emissions. Since these materials possess high structural strength and reduced structural weight simultaneously, their use in the aerospace and automotive industries has the potential to reduce fuel consumption and save energy. For example, recent studies aimed at mitigating climate changes caused by automobiles and by the steel and aluminum industries have shown that a 10% weight reduction results in fuel savings in the range of 4.5 to 6% for vehicles with internal combustion engines.⁴⁶

Porous Asphalt

Most of the exterior noise emitted by modern cars and trucks, particularly at medium to high speeds, is caused by tire/road interaction.⁴⁷ And for automobiles, the A-weighted noise level peaks between about 800 and 1,000 Hz, while for light and heavy trucks, the annoying A-weighted noise level peaks at a somewhat higher frequency in the range of 800 to 1,200 Hz. One way to reduce this noise is by the use of porous road pavement surfaces. These pavement surfaces can be classified as granular sound-absorbing materials. Such surfaces have the advantage that they not only reduce the tire/road noise at the point of its generation, but they also attenuate it (and the power plant noise) by absorption of sound as it propagates to nearby residential areas. Such surfaces have the further advantage that they drain water well and reduce the splash



Figure 5. Sound absorption coefficient of a slab of dense graded Superpave mix with a fine open graded fine core of different thicknesses (t) placed on top.⁴⁸

up behind vehicles during heavy rainfall.

The sound absorption of porous road pavement surfaces is affected by several geometrical and other parameters of the road pavements:

- Thickness of the porous layer
- Air voids (V_q) or road surface porosity
- Air flow resistance per unit length
- Tortuosity
- Coarseness of the aggregate mix (small or large aggregates, etc.)

For most common dense asphalt mixes, the air void (V_a) is about 5%, while for new porous mixes, the V_a content varies from about 15 to 30%.

The sound-absorbing properties of some porous road pavements have been studied by Crocker, et al.48 to reduce interstate highway noise of automobiles. To be able to evaluate the effect of different thicknesses, slabs were manufactured in the laboratory. The slabs consisted of a 6.35-mm dense-graded Superpave mix with a fine 9.5-mm open-graded fine core (OGFC) placed on top. Three different thickness layers were used (2.6 cm, 3.8 cm and 5.1 cm). Figure 5 shows experimental results for the sound absorption coefficient of OGFC samples measured using the standardized two-microphone technique. The thickness of the porous surface has a large effect on the sharpness of the peaks. Generally the thicker the porous surface, the lower the peak frequency. With thicker porous surfaces, the peaks generally also become broader, and the peak absorption is somewhat reduced. For the 5.1-cm sample, the peak frequency is about 900 Hz, which coincides with the noise generated by automobiles in interstate travel in the U.S. In addition, the sound absorption peak is fairly broad, so it is attractive to use such a porous surface to reduce noise.

Micro-Perforated Panels

Perforated panel absorbers have been used for many years in noise control usually to confine porous absorbing materials. When spaced away from a solid backing, a perforated panel is effectively made up of a large number of individual Helmholtz resonators, each consisting of a neck, comprised of the perforated panel and a shared air volume formed by the total volume of air enclosed by the panel and its backing. When the sound waves penetrate the perforated panel, the friction between the moving molecules of air and the internal surface of the perforations dissipates the acoustical energy into heat. The perforations are usually holes or slots, and as with a single resonator, porous material is usually included in the airspace to introduce damping into the system.⁸

When the hole dimensions are in the submillimeter region, however, the absorption peak becomes wider, making the porous absorbing material almost unnecessary. This fact leads to the potential development of transparent sound absorbing materials based on microperforated panels (MPP), long a target in architectural



Figure 6. Calculated example of the absorption characteristics of a thick MPP.⁵² Solid line: hole diameter 0.4 mm, thickness 0.4 mm; Dotted line: hole diameter 0.4 mm, thickness 10 mm; Dashed line: hole diameter 4 mm, thickness 10 mm. Other parameters: perforation ratio 1.0 %, cavity depth 0.05 m.

acoustics.⁴⁹ The basic theory of microperforated panels was presented by Maa in the 1970s, and this theory was further improved in 1997.^{50,51} The theory predicts that when the diameters of the perforations are less than 0.3 mm, enough acoustic resistance and low-acoustic mass reactance is provided to produce wide-band sound absorption. However, further reduction in the size of the holes below a certain value, does not provide a wider absorption bandwidth. Although, the maximum absorption coefficient and maximum possible absorption bandwidth depend on the value of the acoustic resistance, its practical manufacture is limited by the value of the perforate constant. Figure 6 shows Maa's theoretical predictions of the sound absorption coefficient for three different perforated panel absorbers.⁵²

The most important practical challenge is to produce a thin panel having hundreds of millimeter perforations per square centimeter. With the development of finer machinery and advanced manufacturing technologies to form micrometer order holes, such as laser drilling, powder metallurgy, welded meshing and electro-etching, practical fabrication of MPP absorbers is becoming a reality.

Another option suggested for manufacturing an MPP is the use of a fine wire mesh or even fabrics.⁵³ Further developments on both theoretical aspects and practical applications of MPP are currently being investigated, including their nonlinear behavior.^{54,55}

Smart Absorbing Materials

More recently, the use of active noise control⁵⁶ has been combined with passive control to develop hybrid sound absorbers. Active control technologies appear to be the only way to attenuate the low-frequency noise components. Therefore, a hybrid passive/ active absorber can absorb the incident sound over a wide frequency range. Figure 7 shows the principle of such a device, which combines passive absorbent properties of a porous layer and active control at its rear face, where the controller can be implemented using digital techniques.^{57,58}

The use of a piezoelectric actuator as a secondary source and wire meshes as porous material has allowed the design of thin active liners composed of several juxtaposed cells of absorbers to be used to reduce noise in flow ducts.⁵⁸ Recent research has been aimed at producing a broadband sound absorber known as smart foam, which is a hybrid active-passive sound-absorbing material. The absorber is made of melamine foam (made of melamine resin, a thermo set polymer) with Polyvinylidene fluoride (PVDF) piezoelectric-film-embedded actuators. The composite material produces high sound absorption at middle and high frequencies due to the melamine foam's passive properties, while the lowfrequency sound absorption is produced by a classical active cancellation mechanism. Optimization of the sound absorption properties of the smart foam has been developed using threedimensional, finite-element techniques.^{59,60} So a lightweight, thin, efficient sound absorption material can be produced. Another approach involves combining active and passive control using



Figure 7. Hybrid passive/active absorber cell.

microperforated panels. This has given promising results when applied in absorber systems. 61

Conclusions

Porous sound-absorbing materials have evolved into more advanced materials over the years. Compared with the older absorbing materials produced in the 1960s, the new materials have become safer, lighter and more technologically optimized. In addition, the concept of environmentally friendly, sustainable, recycled, and green building materials will soon have an important role in the marketing of sound-absorbing materials. These new directions will hopefully encourage the development of new materials and/or the improvement of existing ones. Given the intensity of research and the development in manufacturing processes, we anticipate that the range of new sound-absorbing materials will expand quickly over the next few years.

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