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Automotive Sound Absorbing Material Survey Results

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ABSTRACT

Recently a sound absorption study was undertaken involving a wide range of samples of common automotive materials from ten different manufacturers. The study included 128 porous absorbers of varying thicknesses and material types (cotton blends, microfibers, etc.). This paper presents the results of that study.

It was found that no single material outperformed all the others; rather, metrics such as specific air flow resistance were more important than the specific material making up the absorber. In general, samples within a certain range of thickness and specific air flow resistance showed the best performance. However, there was no single value of specific flow resistance that was optimal for all material thicknesses. Instead thinner materials required higher flow resistivity than thicker materials. In addition, because the specific air flow resistance is such an important parameter, the presence or lack of a scrim had a significant impact on absorption results.

INTRODUCTION

Three major methods of noise control are used to reduce noise in the interior of the vehicle: (1) reducing noise and vibration sources; (2) applying barriers and other treatments to block sound from entering the passenger compartment, and (3) applying sound absorbers in both the exterior and the interior of the vehicle to dissipate sound and thus reduce the overall sound level.

Inside the vehicle, absorber pads can be effective in a variety of locations. Absorptive materials placed above the headliner, behind the door panel and pillar trim, and under the carpet have proven to be effective.

Porous materials such as foams and fibers are used as absorbers. Viscous losses convert acoustic energy into heat as sound waves travel through the interconnected pores (or fibers) of the material. Because motion of the air through the porous material is necessary to dissipate acoustical energy, a material tends to be ineffective when placed close to a rigid boundary (where the particle velocity is zero). Effectiveness of absorption is directly related to the thickness of the material; absorbers are most effective when their thickness is between one-fourth and one-half the wavelength of the sound, with the maximum performance where the thickness is one-fourth the wavelength. This means that sound absorbers do a very good job at high frequencies, which have short wavelengths. However, at lower frequencies, very thick materials would be required to yield high sound absorption, which would be impractical on the interior of a car.

Recently, two very similar analytical formulations have been developed to describe the sound propagation of porous elastic materials. One theory is the Biot-Allard theory [1], and the other is the Bolton-Shaiu theory [2]. Though independently developed, these two theories are very similar and yield similar predictive results. The theories predict three types of propagating wave in a porous elastic material –the airborne wave, the structure-borne wave, and the shear wave (which is also structure-borne).

The theories demonstrate how the participation of the different types of waves are a function of the boundary conditions [3]. A porous material with an open face or with a porous scrim carries most of the sound energy in the form of the airborne wave. The exception is a porous material that has a structural stiffness less than that of air. In this case, the material behaves as a fluid. In either case, the sound energy can be thought of as being carried by the airborne wave. There are several factors that have a strong influence on the airborne wave, but usually the most important influence is due to the flow resistivity of the material. Most of the materials tested in this study were porous materials with an open or scrim covered face, so the airborne wave is dominant. (For the purposes of this paper, “scrim” will be used to denote a fibrous cover layer with finite flow resistance, and “film” will be used to denote a plastic cover layer with infinite flow resistance.)

A porous material with a non-porous barrier bonded to the face of the material carries the sound energy in the form of the structure-borne wave. The factors that have a strong influence on the structure-borne wave are the bulk stiffness and the structural loss factor.

Specific air flow resistance is determined by measuring the pressure change from one surface of the material to the other at a given flow speed, and is expressed in Pa*s/m, or mks rayls. Flow resistivity is the specific air flow resistance per unit thickness, and in this paper is expressed in mks rayls/mm.

When, in an automotive application, absorption is desired at lower frequencies, and thickness and weight are limited, materials with different specific air flow resistances can be used to achieve desirable results. However, increasing or decreasing the specific air flow resistance to achieve a result at low frequency also has an effect (sometimes adverse) on performance at high frequencies. This paper presents the results of a study of several different materials that illustrate this behavior.

METHODOLOGY

When a sound wave strikes a surface, a fraction of the acoustic energy is absorbed, and the remainder is reflected. The ratio of absorbed energy to incident energy averaged over all possible angles of incidence is the Sabine absorption coefficient (or the random incidence absorption coefficient) of the surface.

The absorption coefficient of a material is measured by introducing a sound source into a reverberant room, terminating the sound source, and measuring the resulting sound field decay. The material is then placed in the room and the measurement is repeated.

To minimize laboratory-to-laboratory variation, purpose built reverberation rooms are used to make standardized measurements. Large-size reverberation rooms allow for longer wavelengths and therefore lower-frequency measurements, but also require large samples (generally 6 m^2 or greater) that can be difficult to obtain. For this reason, the Alpha Cabin (manufactured by Rieter AG) is used by various automotive OEMs. The Alpha Cabin has a total volume of 6.44 m^3, so it requires much smaller samples (1.2 m^2) to generate reliable results. The Alpha Cabin was used for this study.

The Alpha Cabin equipment tests the sample one-third-octave band at a time. First, a burst of sound, band-pass-filtered to a third-octave band, is introduced into the room via three loudspeakers and measured at each of five microphone locations. The sound field decay rate is recorded. Then another burst of sound is introduced, band-pass-filtered to the next third-octave band, and the decay rate measurement is repeated. This process is repeated for each third-octave band from 250 Hz to 10,000 Hz. Results are presented above 250 Hz for this study , but the small size of the Alpha Cabin does not allow enough modes at frequencies below 400 Hz to represent a diffuse field (due to the long wavelengths of sound at frequencies lower than 400 Hz). In other words, results at frequencies below 400 Hz are presented, but should be viewed with a certain amount of caution. The average decay rate is calculated from the individual decay rates at the five microphone positions for each third-octave band.

The sound absorption of the material is given by the following formula:

$$S = 0.163V\left(\frac{1}{T_1} - \frac{1}{T_0}\right)$$

[4] where S is the absorption of the material in metric Sabines, V is the volume of the room in m^3, and T_0 and T_1 are the 60 dB decay times of the room in seconds without and with the material, respectively.

The absorption coefficient is calculated using the following formula:

$$\alpha = 0.92\left(\frac{S}{A}\right)$$

where α is the absorption coefficient and A is the surface area of the material sample. 0.92 is the correction factor to account for the differences between the results in an Alpha Cabin and a full-size reverberation room [4].

Note that measured Alpha Cabin absorption results can exceed the theoretical maximum value of 1.0. This is a result of the assumptions made in deriving the absorption equation to calculate absorption from the measured sound decay times. Sample edge diffraction can also be a contributing factor.

The specific air flow resistance was measured using a commercially available flow meter (Rieter CARE$^+$). This meter is designed to provide a nondestructive measurement of the specific air flow resistance of materials and parts in the range 200 to 4000 mks rayls.

The CARE$^+$ apparatus consists of a housing containing a vacuum pump and instruments which measure pressure and rate of flow. These instruments are connected to a hand-held bell via two tubes. The bell consists of two concentric cylinders through which air is drawn via a vacuum pump. The unit measures the pressure difference once the bell is placed directly over the sample, and the specific airflow resistance of the sample may then be calculated directly from this pressure difference. The measurement differs from the standard ASTM C522 measurement in that the air flow is controlled rather than the pressure drop.

The edges of the sample are not sealed for such a test; however, the use of concentric cylinders ensures an essentially parallel airflow through the material beneath the bell for most of the samples in question. The apparatus includes a “check” to ensure that the pressure difference measured in the outer cylinder and that measured in the inner cylinder are similar; if the two values are not close, it indicates that the airflow through the material is not parallel (due, for example, to air being drawn through the edges of the material), and that the measurement is not reliable. This check was employed for all of the samples tested, and parallel airflow was present in all materials except those with specific air flow resistance out of the range of the CARE$^+$ [5].

The thickness was measured using the Measurematic thickness meter (manufactured by Randen Technologies). The Measurematic measures thickness of a material at a constant pressure between two parallel plates.

STUDY

Ten manufacturers provided a total of 128 materials for evaluation. The materials were supposed to range in thickness from 5 mm to 25 mm; in reality, the thickness ranged from 6.4 mm to 36.5 mm.

Several of the materials were needle punched blends of cotton or plastic fibers (“shoddies”). Many of these consist of post-industrial recycled fibers. Shoddies are shown in Figure 1.

Figure 1. Shoddy

Several blown plastic fiber materials were tested as well. Polyester and polypropylene are common plastic materials used in absorbers. Most of the plastic fiber absorbers tested in this study were made of polyethylene terepthalate (PET). PET fiber products are shown in Figure 2.

Figure 2. PET

Some of the materials were lightweight microfibers. These materials also consist of blown plastic fibers, but have a higher loft and smaller fiber diameters. An example of a microfiber material is shown in Figure 3.

Figure 3. Lightweight Microfiber

Many of the samples were materials with no scrims or embedded layers. However, many of them had scrim or film layers. Some had layers of scrim or barrier embedded inside the material. Several materials with scrim-type layers are shown in Figure 4.

Figure 4. Materials with Scrims

Fiberglass materials were also tested, but not as many of those as shoddy or PET as the former is not commonly used for vehicle interior parts.

The materials are summarized in Table 1.

Supplier	No. of Materials	Material Type	AFR range (mks rayls)	Surface Density Range (g/m^2)	Thickness Range (mm)
A	23	PET	21-2573	428-1748	8-26
B	9	Lightweight Microfiber	279-1643	179-670	7-24
C	17	Shoddy	124-1426	708-1879	11-27
D	12	PET	139.5-High	260-2428	10-27
E	14	PET	139.5-1333	323-1068	7-21
F	16	PET	124-2263	696-1764	7-26
G	13	Fiberglass	62-682	255-634	6-23
H	7	Lightweight Microfiber	124-1054	250-667	10-32
I	4	Shoddy	155-320	672-1215	11-27

J	13	PET	83-816	204-684	7-37

Table 1. Material Descriptions

RESULTS

For brevity's sake, the results of all 128 materials are not given in detail. However, the results of the ten best and ten worst performers are presented in Tables 2 and 3. The air flow resistivity (specific air flow resistance divided by thickness), thickness and surface density values are presented as well.

Material	Flow Resistivity (mks rayls/mm)	Thickness (mm)	Surface Density (g/m^2)	Scrim/Film	Averag e alpha
D8	39.6	27	1998	Scrim*	0.942
B10a	68.6	24	670	Scrim	0.939
H7	33.3	32	666	Scrim	0.925
H5	33.5	31	667	Scrim	0.919
B8a	80.0	19	538	Scrim	0.909
D10	21.1	25	1455	Scrim	0.898
C17	35.0	27	1879	No*	0.897
H6	35.3	25	510	Scrim	0.891
D12	61.9	27	2428	Scrim*	0.886
B9a	38.3	20	508	no	0.873

*D8, C17, D12: Dual layer shoddy, scrim between layers (if applicable)

Table 2. Best Performers

Material	Flow Resistivity (mks rayls/mm)	Thickness (mm)	Surface Density (g/m^2)	Scrim/Film	Averag e Alpha
A1	7.0	9	458	No	0.413
A5	6.6	9	473	No	0.419
E1	21.9	7	597	No	0.420
G3	10.7	9	259	No	0.451
A9	3.9	16	450	No	0.475
A3	34.6	8	1049	No	0.482
G1	38.6	6	317	No	0.484
JC	13.5	7	204	No	0.486
G9	5.2	12	255	No	0.494
A19	2.0	24	455	No	0.499

Table 3. Worst Performers

Typically, the noise reduction coefficient (NRC) is used as a single index of absorption capability. The NRC is an average of the absorption coefficients at 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. However, because the Alpha Cabin only yields results down to 400 Hz, and because high frequency performance is to be given detailed consideration in the case of this study, the values at each third octave frequency from 400 Hz and 10,000 Hz are averaged to give a more accurate single-number representation of the materials' performance in the Alpha Cabin.

A few initial observations can be made from Tables 2 and 3. No single material construction stood out as the best (or worst) absorber. Plastic fibers can have very good or very poor absorptive qualities. Several of the best absorbers were lightweight fibers, and several of the worst absorbers were fiberglass, but several of these materials also ended up in the middle of the pack. A similar observation can be made about surface density: while the best performers had higher overall surface densities than the worst performers, both sets contain samples with a wide range of surface densities.

Eight of the 128 materials are discussed in greater detail below. The specifications of these samples are given in Table 4. These samples represent neither the best nor the worst performers, but illustrate attributes that contribute to the absorption performance.

Material	Flow Resistivity (mks rayls/mm)	Thickness (mm)	Surface Density (g/m^2)	Scrim/ Film	Averag e Alpha
E14	10.0	19	443	No	0.705
A19	2.0	24	455	No	0.499
B4a	78.3	10	279	Scrim	0.755
H1	11.7	11	250	No	0.531
F3	206.7	7	702	Scrim	0.601
E1	21.9	7	597	No	0.420
D11	168.0	28	1958	Scrim	0.650
F16	68.6	26	1001	Scrim	0.767

Table 4. Sample details

There is a strong trend where the thickest samples had the highest absorption and the thinnest samples had the lowest absorption. This is expected when the sound absorption is dominated by the airborne sound wave as described above. However, this trend was not hard and fast. An example of an exception can be seen in Figure 5, which shows how sample E14, at 19 mm, outperformed sample A19 at 24 mm.

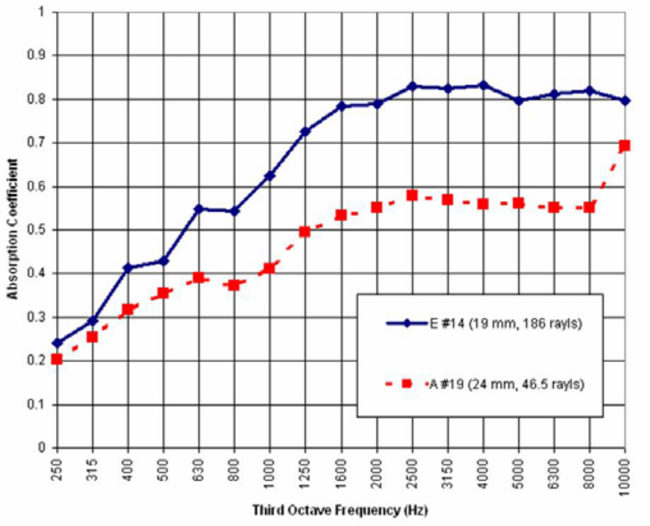

Figure 5. Exception to Thickness Trend

It is noteworthy in the above example that the specific air flow resistance of A19 was lower than that of E14. This phenomenon indicates that both thickness and specific air flow resistance must be taken into account when considering the performance of a material.

As stated above, the specific air flow resistance in mks rayls divided by the thickness in millimeters is the flow resistivity, which for the materials in this study ranged from 1.3 to 295 mks rayls/millimeter (as well as some materials for which this value could not be calculated due to off-the-charts air flow resistance values). The best performers were the thickest materials with flow resistivity values within a specific range. Some of the worst performers had a flow resistivity in the same range, but were so thin that they were not able to absorb much sound across the frequency spectrum. Likewise, some of the worst performers were typical thicknesses used in automotive applications (15-25 mm), but their flow resistivity was low (in the case of A9 and A19, shown in Table 3, less than 10 mks rayls/mm).

When all of the samples are examined, it is evident that the thinner the sample, the higher the flow resistivity required to yield high absorption. Compare F3 to B4a in Figure 6 below. In fact, a flow resistivity that might be too high in a thicker sample yields desirable absorption results in a thin sample – particularly when compared with a sample of similar thickness but low flow resistivity. This phenomenon can also be seen in Figure 6, where B4a outperforms H1, and F3 outperforms E1, in spite of comparable thickness.

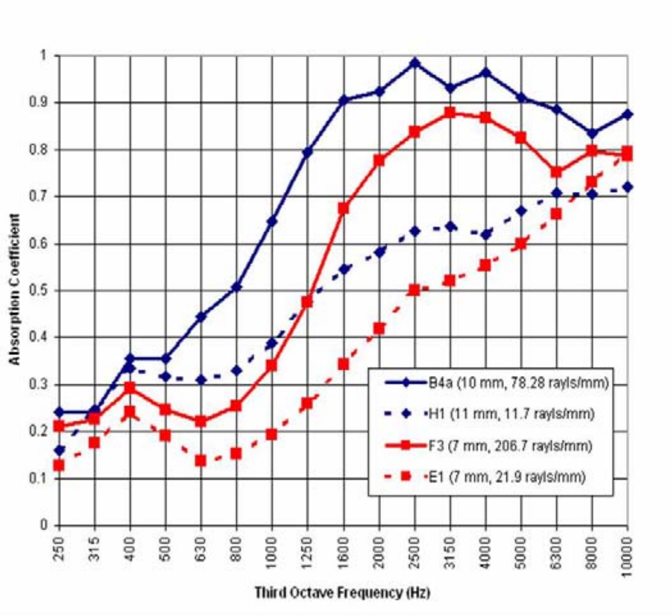

Figure 6. Flow Resistivity vs. Thickness

To dissipate sound, a sound absorber must perform two functions. First, it must admit the sound into the material, and then it must dissipate the sound as it travels through the material. The two functions represent competing demands of the material. The first function relates to the acoustic impedance of the front face, because the impedance mismatch causes sound to be reflected from the front face of the material. As the material is made thinner, more flow resistivity is required to dissipate the sound because the dissipation must take place in a shorter distance. Thus, higher flow resistivity becomes much more important as the material is made thinner.

If a thicker sample is relatively thick (25 mm and above) it might be able to overcome a low flow resistivity, but if the resistivity is too high, the absorption will be compromised at higher frequencies, as shown in Figure 7. (However, in some cases absorption at lower frequencies is more of a priority.)

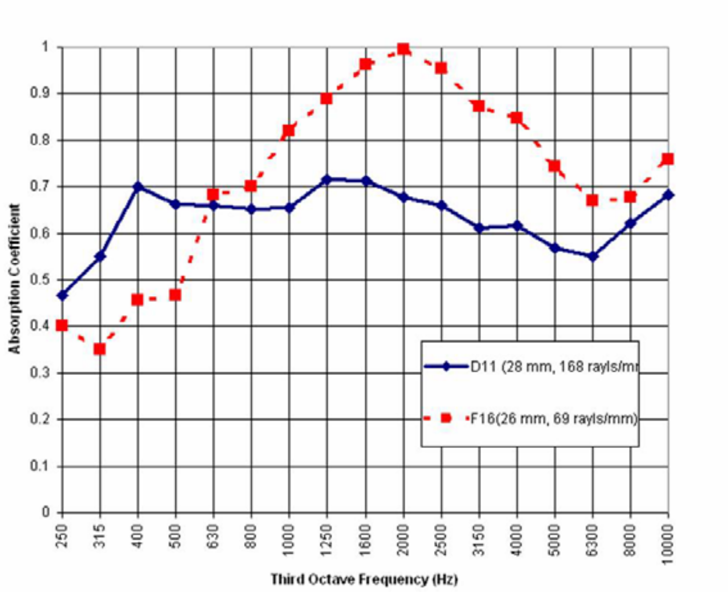

Figure 7. Effect of High Flow Resistivity

The overall trends for all 128 of the samples support the conclusion that higher flow resistivity is required for thinner samples, as shown in Figure 8, which plots flow resistivity against average alpha for thin and thick samples.

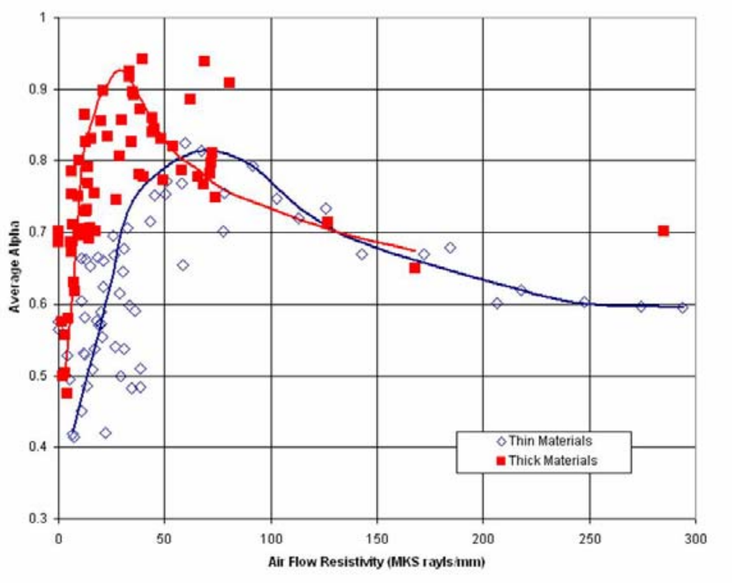

Figure 8. Flow Resistivity vs. Average Alpha: Trends

It is evident from Figure 8 that thin and thick materials have different ranges of flow resistivity that yield high absorption. In addition, Figure 9 below shows the relationship between specific air flow resistance and average alpha of all 128 materials.

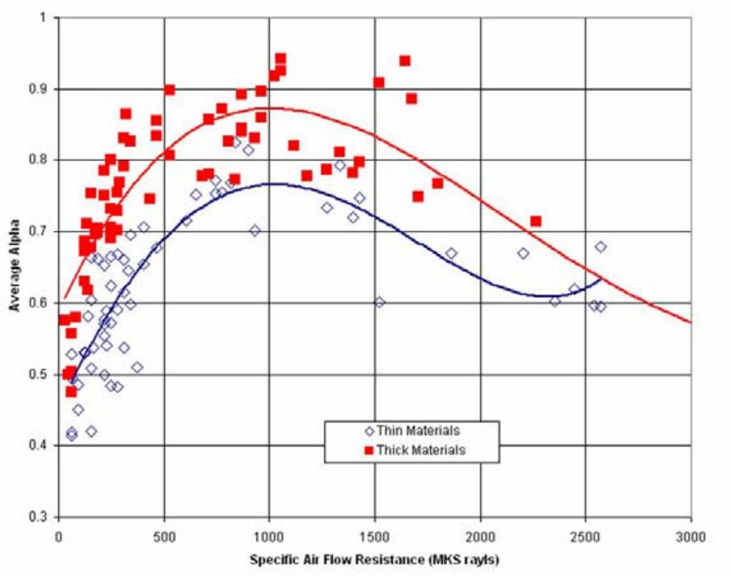

Figure 9. Specific Air Flow Resistance vs. Average Alpha: Trends

It is clear that regardless of thickness, the specific air flow resistance that yields the highest absorption is around 1000 mks rayls. It is also noteworthy that for thicker materials, a wider range of specific air flow resistance can yield good results than for thinner materials.

CONCLUSION

The results show that sound absorption performance of the porous materials used in automobiles is not so much a function of type of material (cotton shoddy, PET, or fiberglass), as it is a function of how well the material construction can be executed to achieve desirable properties for sound absorption. For open faced materials or materials with a porous scrim, the flow resistivity is very important. Put another way, what a porous material is made of is less important than how economically it can be processed to have desirable acoustic properties.

The best material properties are a function of the application such as the material thickness and boundary conditions. Thinner materials require significantly more flow resistivity than thicker materials; therefore, materials that are nearly optimal in one application may not work well in another application. However, a specific air flow resistance of around 1000 mks rayls can yield good overall absorption regardless of the thickness of the material.

Material properties may be adjusted to produce more absorption in one frequency range than another. For example, the flow resistivity of a material may be increased to improve absorption at lower frequencies at the cost of lower absorption at higher frequencies.

One common method of increasing flow resistivity is the addition of a flow resistant scrim or film layer, which increases the specific air flow resistance without adding too much weight or thickness. It is also possible to increase the flow resistivity by increasing the surface density of the material (adding density without changing the thickness); however, this method adds weight, which may be an issue in automotive applications.

In general, there is a wide range of acoustical performance of different materials available for sound absorption in the interior of an automobile. As material changes are made, the performance of the materials needs to be carefully compared either by modeling, material testing, and/or vehicle testing.

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