Basic Study for Acoustic Absorption Characteristics of Soft and Light Granular Material*

(Basic Characteristics for Expanded Polystyrene Beads)

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Abstract

In this paper fundamental sound absorption characteristics of expanded polystyrene beads with several geometries are reported when they are packed in some thick layers with and without back air space. The normal incidence sound absorption coefficients, which were obtained by the experiments using two-microphone impedance tube, were evaluated comparing to theoretical estimations. Experimental data were also compared to the similar conditions but hard material particles like glass beads whose acoustic property was investigated by Sakamoto et. al. in a preceding study. Then following results were obtained: packed layer with expanded polystyrene beads has almost equal sound absorption coefficient to the similar layer with hard and solid material: numerical estimation of sound absorption coefficient is valid enough except for the case having large back air space: lowering peak frequency of sound absorption coefficient is available by overfilling and compressing particles. The authors also consider that applying soft, light, and low cost material to the sound absorbing structures is very meaningful. Because human damage caused by falling of wall and ceiling panel of buildings is avoidable particularly under an earthquake attack.

Key words: Sound and Acoustics, Noise Control, Porous Media, Material Design, Absorption Coefficient, Multilayer, Back Air Space, Impedance Measurement Tube, Ceiling Material

1. Introduction

Collapse of ceilings in facilities constructed at a height such as indoor pools, public bathhouses, and auditoriums has dangerous consequences. Such cases of collapse of the ceiling from a height during earthquakes have been reported. For instance, injuries due to an indoor pool ceiling collapse were reported in the 2005 16th August Miyagi earthquake, and some fatal accidents due to an auditorium ceiling collapse were reported in the 2011 11th March the Great east Japan earthquake. Therefore, the Japanese government determined to remove the false ceiling of the gymnasium in all the public schools from 2013 May. Even in normal circumstances, humid places with high ceilings, such as pools and public bathhouses, carry a high risk of ceilings collapse because of a decrease in the strength of the materials. In such an environment, a soft and light interior ceiling material would be useful,
and a sound-absorbing material would be a better option. Lightweight ceilings also decrease the weight load on buildings, contributing to an improvement in seismic resistance. Glass cloth is one of the proposed ceiling materials that are soft, light, and sound-absorbing\(^{(1)}\).

In previous studies\(^{(2)}\)(\(^{(3)}\), we reported the results obtained from the evaluation of the sound-absorption coefficient using spherical glass beads as the typical geometric shape for a granular material. Such sound attenuation occurs because of friction due to viscosity at the boundary layer on the surface of particles, which is the case in a porous sound-absorbing material with continuous pores.

In this report, we use expanded polystyrene (EPS) as the light granular material. The bulk density of this material is approximately 10 times the density of air. Even if EPS falls, the fall velocity would be small because the drag force per weight is considerably larger than other heavier material, and even if it falls on a person, no harm is inflicted because it is generally used as a packing material. We measured sound-absorption coefficient of this material with and without back air space, for several beads sizes and layer thickness. We then compared the results with glass beads of the same geometric size. We also investigated the changes in the sound-absorption properties due to the weight-induced deformation of the EPS beads.

2. Methods and Test Samples

2.1 Measurement device for the normal incidence sound-absorption coefficient

Fig. 1 shows the schematic view of the measuring equipment. We used Brüel & Kjær Type 4206 Impedance Tube for the measurement. The test samples were sealed at the end of a tube. In this set up, a swept sine signal is produced by a signal generator equipped with an FFT analyzer, and a loudspeaker emits sound waves into the tube. The FFT analyzer evaluates the transfer function between the sound pressure signals measured by two microphones. Using this transfer function, we evaluated the normal incidence sound-absorption coefficient in accordance with Japanese Industrial Standards A 1405-2. The sound pressure level in the tube during sweep varies depending on the frequency and sound pressure distribution, but it was within the range 94–113 dB. A practical situation would be most likely random incidence; hence, the actual sound absorption performance is higher than the measurement results, as is the case in general porous sound-absorbing material.

The limit frequency of plane waves in the tube depends on the diameter of the tube. The range of the limit frequency for measurement is 50–1600 Hz for a large tube having an internal diameter of 100 mm and 500–6400 Hz for a small tube having an internal diameter of 29 mm. Therefore, for combining the measurement results of the large and small tubes,
the frequency range used for the large and small tubes were 50–675 and 1450–6400 Hz, respectively, and the average of the values of the large and small tubes for an octave of 700–1400 Hz was considered for measurement results, as per Japanese Industrial Standards A1405-2.

2.2 Object

The objects used in the experiment include solid EPS beads. Table 1 shows the nominal size, diameter range, bulk density, and per-piece weight of the granules used in the experiment, and Fig. 2 is the corresponding image. Under the test, the bulk density of these EPS beads are similar to that of the glass wool felt categorized into code: GW-F by JIS A6301-2007.

To prepare test samples of varying thicknesses in increments of 10 mm with a back air space, the necessary number of parts thickness of 10 and 20 mm as shown in Fig. 3 are combined for obtaining necessary thickness. The test sample is then attached to one end of the impedance measurement tube.

Table 1  Expanded polystyrene beads under the test

<table>
<thead>
<tr>
<th>Nominal size [mm]</th>
<th>Spherical φ4</th>
<th>Spherical φ2</th>
<th>Spherical φ1</th>
<th>Cubic 0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range of filter mesh [mm]</td>
<td>3.35–4.75</td>
<td>1.7–2.36</td>
<td>0.85–1.18</td>
<td>---</td>
</tr>
<tr>
<td>Bulk density [kg/m³]</td>
<td>8.6</td>
<td>16.4</td>
<td>32.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Average weight per one particle [μg]</td>
<td>522</td>
<td>151</td>
<td>34.9</td>
<td>4.98</td>
</tr>
</tbody>
</table>

Fig. 2  Photograph of each kind particle
(from left side φ4, φ2, φ1 and cubic 0.8mm)

Fig. 3  Equipments for test sample
To evaluate the flammability of this material, a fire retardant used in construction-grade styrene resin can be utilized. Assuming the bulk density to be 10 kg/m$^3$, a 50-mm-thick EPS bead layer is equivalent to a 0.5-mm-thick resin board in quantity, implying that the quantity of EPS as a flammable material is equivalent to that of a coating film. There is a technique for converting the disposed EPS foam back into polystyrene beads; thus, it is possible to use recycled materials for sound absorption.

3. Normal Incidence Sound-Absorption Coefficient with a Rigid Wall Behind

3.1 Results for normal incidence sound-absorption coefficient

Figs. 4–6 show the results obtained from the evaluation of the normal incidence sound-absorption coefficient. The measurements were performed for granular sizes of 1, 2, and 4 mm with varying layer thicknesses. The measurement results for glass beads under the same conditions are also shown. Compared to glass beads of the same geometry, EPS beads have almost the same sound-absorption properties, although they tend to have higher absorption peak frequencies. Considering that the bulk density of EPS beads is around a hundredth that of glass beads$^2$, EPS beads are useful as a sound-absorbing material.

Fig. 4  Comparison between expanded polystyrene beads and glass beads ($\phi$ 1)

Fig. 5  Comparison between expanded polystyrene beads and glass beads ($\phi$ 2)

Fig. 6  Comparison between expanded polystyrene beads and glass beads ($\phi$ 4)
The peak frequency for sound absorption depends on layer thickness because the sound-absorbing effect increases when the surface of the porous material is located where the particle velocity is large\(^6\).

Under the test, 50-mm-thick EPS beads with rigid wall backs (Fig. 4) are categorized as approximately “0.3M” grade of sound absorption performance by JIS A6301-2007. On the other hand, glass wool felt (code: GW-F) is categorized as “0.7M” grade, which is better than that of EPS beads.

### 3.2 High-expansion cubes with 0.8 mm sides

While 1-mm EPS beads are superior in sound-absorption performance, their bulk density is higher than that of beads of other sizes. If 1-mm EPS beads had a higher expansion ratio, they will be lighter and less flammable in its quantity. However, since high-expansion 1-mm beads were not commercially available, we made cubic granules by hand from an EPS board having a high expansion ratio. The cubes were 0.8 mm in size on each side. The properties of these granules are shown in Table 1. Since it was difficult to obtain a large number of granules, measurements were performed only with the small tube for sample thicknesses of 10, 20, and 30 mm.

The results are shown in Fig. 7. For comparison, the results for 1-mm EPS beads are also shown. They have similar sound-absorption properties, indicating that high-expansion 1-mm beads would be a lighter sound-absorbing material.

Fig. 7 also shows that the sound-absorption coefficient curves for the 0.8-mm cubic granules are shifted to lower frequencies and have peaks lower than those for the 1-mm spherical granules. The shift to lower frequencies may be because the sound velocity in the sound-absorbing material decreased owing to the small size of the granules. The decrease in the value of the peak sound-absorption coefficient is attributed to a decrease in the value of the sound-absorption coefficient owing to an increase in the incident impedance when the granule size becomes too small\(^2\).
4. Normal Incidence Sound-Absorption Coefficient with a Back Air Space (2)

As shown in Fig. 8, we measured the normal incidence sound-absorption coefficient of an EPS bead layer with a back air space. Fig. 9 shows the sound-absorption coefficient for each thickness value of the back air space. Similar to the case of general porous sound-absorbing materials, the peaks of the sound-absorption coefficient shifted to lower frequencies as the thickness of the back air space increased.

In Fig. 10, the experimental results are compared to the computational results (2) on the basis of the acoustic constant obtained from the two-thickness method (3). The calculated values are close to the experimental values. This implies that similar to the case of glass beads, if the acoustic constant is obtained in advance, then we can also estimate the sound-absorption properties of this material under unmeasured conditions, such as different thicknesses and layer states.

However, similar to the case of the 40-mm back air space, as the thickness of the back air space increases relative to that of the granular material layer, differences between the calculated and experimental values tend to increase.

Under the test, EPS beads with back air spaces (Figs. 9 and 10) are categorized as approximately “0.5U” grade of sound absorption performance by JIS A6301-2007. On the other hand, perforated boards for ceilings or walls (code: GB-P, AC-P, and HB-P) are categorized as “0.3U” grade, which is lower than that of EPS beads.
5. Normal Incidence Sound-Absorption Coefficient When Stacking Different Granular Sizes

As shown in Fig. 11, we added EPS of different granular sizes to the upper and lower layers, whose total thickness was 50 mm. Under these conditions, we measured the sound-absorption coefficient.

In a previous study\(^2\), it was shown that when the granular size is less than 1 mm using the larger size for the upper layer results in impedance matching with air, leading to an increase in the value of the sound-absorption coefficient over a wide range of frequencies. Fig. 12 shows experimental results for varying layer thicknesses. In each case, 1-mm EPS beads were used for the lower layer and 4-mm beads were used for the upper layer. When the lower layer contained 1-mm beads, the sound-absorption coefficient decreased drastically as the thickness of the 4-mm upper layer increased. This indicates that multilayering is not beneficial.

![Expanded polystyrene beads](image)

**Fig. 11** Schema of test sample (multi layer)

![Graph](image)

**Fig. 12** Variation depends on thicknesses of each layer (upper layer \(\phi \ 4\), lower layer \(\phi \ 1\))

![Graph](image)

**Fig. 13** Variation depends on thicknesses of each layer (upper layer \(\phi \ 1\), lower layer \(\phi \ 4\))
Fig. 13 shows the experimental results when 1-mm EPS beads were used for the upper layer. Even when used in a single layer, a granular size of about 1 mm shows good peak sound-absorption coefficients. When 1-mm beads were used for the upper layer in multilayer stacks, there was a slight decrease in performance while increasing the thickness of the lower 4-mm bead layer. This indicates that use of expensive small beads can be reduced while maintaining performance.

Moreover, when used as a ceiling material, the layers are oriented upside down, so the fine, dense, and small beads are on the lower side, i.e., the plane of incidence. Even without a separator to divide layers of different granular sizes, both types of granules are likely to stay separated because of their densities and sizes. Furthermore, it is easy to create a back air space for a ceiling material, through which the sound-absorption performance is further improved.

6. Changes in Sound-Absorption Properties for Compressed Test Samples

6.1 Compressing test samples assuming as ceiling material

Fig. 14 shows a schematic view of EPS beads used as a ceiling material. In the case of Fig. 14 (a), under certain conditions (e.g., if the ceiling is tilted), the desired layer thickness cannot be maintained by simply filling EPS beads inside the surface material of the ceiling. As shown in Fig. 14 (b), this problem may be solved by holding the beads with an acoustically negligible coarse fabric in a quilt-like manner. Many choices are available for the material to use for suspending or holding the beads in this manner, including nonflammable mesh fabrics and thin filter materials.

Since EPS beads are soft, when they are added to the cells of a quilt, the granules are deformed, even if the compression force is small. We investigated such geometric changes in the gaps between beads. Since the sound-absorption coefficient is significant only at high frequencies when there is no back air space, we use the results obtained from the small tube for this discussion. In the series of experiments, multiple measurements were done for each condition to confirm reproducibility. We measured each multiple with the same group and same number of beads, particularly in the case of bead compression.
6.2 Surface material for compression

Fig. 15 shows a schematic view of the test sample to be compressed with an acoustically negligible material. Before compression, EPS beads were filled thicker than the desired thickness. We tested two surface materials: (1) a thin stainless steel wire gauze (30 mesh, wire diameter 0.3 mm, opening 41.7%) and (2) a 0.8-mm thick aluminum perforated panel (hole diameter 3 mm, opening 32.6%). Both of them are generally used for surface protection of glass wool. We tested these two types of surface materials to ensure that the effects of the opening ratio and vibration of the surface material are sufficiently small.

![Fig. 15  Schema of pressed test sample](image)

6.3 Acoustic transparency of the surface material

First, we tested the acoustic transparency of these surface materials. To eliminate the possibility that the granular layer was affected by vibrations of the surface material, we made a gap between the surface material and the EPS layer. The layer thickness was 48 mm and the surface material was located at 50 mm, so there was a gap of about 2 mm between them.

Fig. 16 shows experimental results for 4-mm EPS beads. The results obtained by using the wire gauze, perforate panel, and neither of the two were almost the same. Therefore, these surface materials are sufficiently acoustically negligible.

![Fig. 16  Comparison of acoustic penetration between with and without surface material (φ4mm, layer of thickness 48mm)](image)
6.4 Effects of compression force by the surface material

Glass beads are not deformed even when compressed. Therefore, we can use them to investigate the effect of restraining the granules by an applied compression force, while eliminating the effect of deformation of the beads.

We placed the 4-mm glass beads into the equipment shown in Fig. 3 with a minimal projection (about 2 mm) from the layer thickness of 50 mm. A compression force was then applied by placing the wire gauze at the 50-mm position. In this experiment, the wire gauze exhibited elastic deformation.

Fig. 17 shows the experimental results for 4-mm glass beads with and without the compression force applied by the wire gauze. The results do not change when the beads were restrained by compression.

6.5 Compression of EPS beads by the surface material

Fig. 18 shows the experimental results for the sound-absorption coefficient of 2-mm EPS bead test samples compressed to a layer thickness of 50 mm by the wire gauze and by the perforate panel. It was difficult to precisely control the “compression margin” because keeping every bead on the surface of the test sample at the same height is difficult. However, in this case, the compression margin was about half the granular size. For comparison, the results obtained without the surface material are also shown.
When the EPS test sample was compressed by the wire gauze, unique absorption spikes appeared around 2200 Hz, as shown in Fig. 18. These absorption spikes did not appear when the perforate panel was used or when glass beads were compressed with the wire gauze, as shown in Fig. 17. Thus, the absorption spikes in Fig. 18 appear specifically when soft EPS beads were compressed with the thin wire gauze, suggesting that the two might be creating coupled vibrations. Hence, in the following experiments, to observe the sound-absorption properties of EPS beads alone, we use the results obtained with the use of the perforate panel.

Fig. 19 shows the images taken from the sides of the 2-mm bead, 50-mm thick test samples with minimum and compression margins one-bead thicker. When using the 50-mm-thick test samples, for any granular size, the minimum compression margin was about half the granular size. The compression margin was slightly greater than the granular size when the test sample was made one bead thicker.

6.6 Compressing EPS beads with the perforate panel

Figs. 20–22 show the experimental results obtained from the evaluation of sound-absorption coefficients for each granular size; the test samples were compressed to a layer thickness of 50 mm by the perforate panel. For comparison, the results obtained without the surface material, that is, without compression, and those obtained with glass beads are also shown. For granular sizes of 2 mm or less, to keep the beads from passing through the 3-mm holes of the perforate panel, we inserted a rough synthetic fiber mesh material between the perforate panel and the bead layer.

Comparing the results obtained in the absence and presence of compression (i.e., the first two items and the third item in the legends of Figs. 20–22), when test samples were compressed, the absorption peak at a low frequency shifted to a lower frequency. This is probably because the gaps between beads narrowed, thus decreasing the sound velocity (3).

For granular sizes of 2 and 4 mm, the sound-absorption coefficient at the peaks increased. This is probably because compression narrowed the gaps between the beads, and the sound-absorption effect due to viscosity of the boundary layer increased. For a sound-absorbing material, this is a desirable property change. However, for a granular size 1 mm, the peak values of the sound-absorption coefficient decreased after compression. Similar in case of the cubic granules shown in Fig. 7, this is probably because the gaps between beads became too narrow.

Next, comparing the “large and small compression margins” (i.e., the first and second items in the legends of Figs. 20–22), it is indicated that the larger the granular size, the larger the difference in sound-absorption coefficient value due to the margin difference. This is probably because the increase in the layer thickness due to the added bead layer is larger for larger granules, resulting in more changes in the compression ratio.

Finally, we compare the EPS results with those for glass beads (the fourth item in the legend). It appears that the results obtained from glass beads lie between the results obtained with (the first and second items in the legend) and without (the third item in the legend) compression. This may be explained as follows. Since EPS beads are light, even if
shaken when filled in a container (since the balance between self weight and surface friction differs from glass beads), they do not get compressed to the limit, leaving some gaps between beads. Consequently, in the early stages of compression, the experimental results become similar to those for glass beads because the gaps between beads become narrow without deformation. Subsequently, when the beads start to deform (as if passing through the results of glass beads), the frequencies of the absorption peaks decrease further.\(^{(3)}\)
7. Conclusion

In this study, we examined the acoustic properties of materials composed of expanded polystyrene (EPS) beads and obtained the following results.

(1) EPS beads have sound-absorption properties that are similar to those of hard glass beads. In addition, as a construction material, they have high thermal insulation properties and low production costs. They are also light, indicating that they exert less load on building supports and their collapse during an earthquake does not cause any harm. Under the test, EPS beads that are 50-mm thick with rigid wall backs are categorized into approximately “0.3M” grade of sound absorption performance by JIS A6301-2007, whereas those with back air space are categorized into approximately “0.5U” grade. However, these measuring results were normal incident absorption coefficient, so the absorption coefficient by the reverberation room method for these EPS beads are higher than these measuring results.

(2) We used actually measured acoustic constants to estimate the normal incidence sound-absorption coefficients for layers of EPS beads having a back air space and compared these estimates with experimental results. This enables us to make estimates even for unmeasured conditions, although the differences between estimates and experimental values increase as the thickness of the back air space increases.

(3) When using EPS beads as a ceiling material, placing a layer of about 1-mm beads at the plane of incidence and a layer of larger beads above it can maintain the sound-absorption performance while using only small amounts of expensive small beads.

(4) When an EPS bead layer is compressed, the sound velocity appears to decrease as a result of narrowed gaps between beads, and the frequency characteristics of the sound-absorption coefficient shift to lower frequencies. Because this behavior is desirable in sound-absorbing materials, it provides a positive benefit.

References

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