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The development of sound absorbing materials using natural bamboo fibers

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Abstract

An acoustic material has been newly developed from the viewpoint of environmental protection. For this purpose, we used a natural resource, bamboo fiber, to manufacture sound absorbing material. In this paper, the normal incidence sound absorption coefficient of bamboo fiber material was measured at the influences of thickness, air space depth, apparent density and the bamboo fiber diameter using an impedance tube. In addition, the characteristic impedance and the propagation constant of the materials were measured. The results showed that the bamboo fiber material has acoustic properties equivalent to those of glass wool. The sound absorption coefficient increased with an increase in density. We also attempted to find the best combination of samples of different densities to improve the sound absorption effects. A high sound absorption coefficient was obtained when higher density material was placed on the side of the sound source. Also, a fiberboard was made using the bamboo fiber to create the surface material of the bamboo fiber material, and was compared with plywood of the same density. The sound absorption coefficient of the bamboo fiberboard and the resonance-type bamboo fiberboard was found to be superior, especially in the high frequency range. Consequently, fundamental design criteria have been confirmed using the newly developed bamboo fiber material for sound absorption.

1 Introduction

Acoustic material plays a number of roles that are important in acoustic engineering such as the control of room acoustics and traffic noise. Acoustic materials are divided into three kinds of material: a porous material, a board, and

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a resonance-type board. Porous materials are the most effective for noises that have over the broadband frequency range. Acoustic materials have been developed for their use in sound absorption. On the other hand, acoustic material is claimed to have additional benefits, such as energy conservation, the advanced use, and re-use of resources from the viewpoint of earth protection [1]. Health concerns have been raised over glass fibers that become airborne and adhere to the body during building construction. Because, glass wool is not the best material, we adopted a bamboo fiber from natural resources for the protection of human health and the environment. We can harvest bamboos every year because young bamboo grows quickly. The bamboo is effective as a resource because it is natural and the waste product is simple. There is no anxiety over ground pollution even if it is buried in the earth and it does not emit poisonous fumes even if it is burned. In this paper, an alternative sound absorbing material is developed that alleviates the load on the environment.

2 Performance of acoustic material

2.1 Performance of porous material

The performance of sound absorbing material is evaluated by the sound absorption coefficient, which is defined as the ratio between the absorbed and the incident sound energy. For rigid-framed porous material, this absorption is mainly attributed to thermo elastic damping and viscose loss generated while the sound propagates through a large number of small air cavities in the material. In order to clarify the acoustic effect in the material, use of the sound absorption coefficient alone is not sufficient to determine the internal structure of the acoustic material. It is necessary to know the state of the sound wave propagation in the material. Measurement of the characteristic impedance and the propagation constant enables us to determine the state of the reflection and attenuation of the sound wave [2].

2.2 Definition of sound absorption coefficient

As shown in Figure 1, when the plane wave perpendicularly goes from media A to the boundary surface of media B, sound absorption is defined as follows,

$$a = 1 - \frac{R}{I} = \frac{I - R}{I}, \tag{1}$$

where I is the incident energy, R is the reflection energy, and I/R is the ratio of both energies. The boundary surface has two conditions that the particle speed and the sound pressure are equal to on both sides:

$$p_i + p_r = p_t, \tag{2}$$

$$v_i - v_r = v_t. \tag{3}$$

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The two formulas should be satisfied at the same time.

$$\frac{p_i}{Z_A} - \frac{p_r}{Z_A} = \frac{p_t}{Z_B}, \tag{4}$$

where, $Z_A = \rho_A c_A$ and $Z_B = \rho_B c_B$. The sound pressure reflection ratio r_p is

$$r_p = \frac{p_r}{p_i} = \frac{Z_B - Z_A}{Z_B + Z_A}. \tag{5}$$

The sound energy is proportional to $|p_i|^2$ and $|p_r|^2$, respectively:

$$\frac{R}{I} = \frac{|p_r|^2}{|p_i|^2} = |r_p|^2, \tag{6}$$

$$a = 1 - |r_p|^2 = 1 - \left|\frac{Z_B - Z_A}{Z_B + Z_A}\right|^2, \tag{7}$$

where a is the sound absorption coefficient, and when media A is an air and media B is a sound absorbing material, $Z_A = \rho c$ and $Z_B = Z$ are replaced,

$$a = 1 - \left|\frac{(Z/\rho c) - 1}{(Z/\rho c) + 1}\right|^2. \tag{8}$$

2.3 Sound behavior in the absorbing material

As shown in Figure 2, when sound waves are attenuated in the absorbing material, p_0 is the sound pressure with point $x = 0$, and the sound pressure of the plane wave that goes in the x axis direction is

$$p = p_0 e^{-\gamma x}$$
$$\gamma = \alpha + j\beta, \tag{9}$$

where, γ is the propagation constant, α is the attenuation constant, $\beta = \omega / c$ is the phase constant, and c is the sound velocity in the material. When it is not attenuated, β is the wave constant k. The velocity part of the homogeneous material is

$$v = -\frac{1}{j\omega\rho}\frac{\partial p}{\partial x}. \tag{10}$$

The characteristic impedance at normal incidence is

$$Z_c = \frac{p}{v} = \frac{j\omega\rho}{\gamma}. \tag{11}$$

The propagation constant and the characteristic impedance completely determine

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the state of the sound wave.

When the homogeneous layer has the thickness L, the characteristic impedance Z_c, and the propagation constant γ, the sound wave is

$$p(x) = p_i e^{\gamma(L-x)} + p_r e^{-\gamma(L-x)}, \tag{12}$$

$$v(x) = \frac{p_i}{Z_c} e^{\gamma(L-x)} - \frac{p_r}{Z_c} e^{-\gamma(L-x)}, \tag{13}$$

where, p_i is the sound pressure of the direction of the positive of x and p_r is the sound pressure of the negative at $x = L$. When this layer has an acoustic impedance Z_2 in the back, the acoustic impedance at $x = 0$ is

$$Z_1 = Z_c \frac{Z_2 \cosh\gamma L + Z_c \sinh\gamma L}{Z_2 \sinh\gamma L + Z_c \cosh\gamma L}. \tag{14}$$

When the layer has a rigid wall in the back, $Z_2 = \infty$,

$$Z_1 = Z_c \coth\gamma L. \tag{15}$$

When the layer has the air space depth L_0 in the back,

$$Z_1 = -jZ_0 \coth kL_0, \tag{16}$$

where Z_0 is the characteristic impedance of air. Using eqns (8) and (14), the sound absorption coefficient can be calculated from the acoustic impedance of the material surface [3].

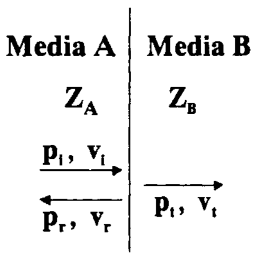

Figure 1: The sound behavior to media B from media A.

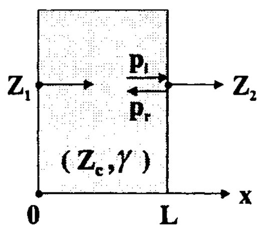

Figure 2: The sound behavior in the absorbing material.

3 Measurement method

We used a measurement system introduced by Utsuno, et al. [4], as shown in Figure 3. The acoustic impedance Z_1 at a reference surface can be related to eqn (14). Z_c and γ can be represented as follows

$$Z_c = \pm\left(\frac{Z_1 Z_1'(Z_2 - Z_2') - Z_2 Z_2'(Z_1 - Z_1')}{(Z_2 - Z_2') - (Z_1 - Z_1')}\right)^{1/2}, \tag{17}$$

$$\gamma = \frac{1}{2jL} \ln\left(\frac{Z_1 + Z_c}{Z_1 - Z_c}\frac{Z_2 - Z_c}{Z_2 + Z_c}\right), \tag{18}$$

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where the sign in eqn (17) is selected so as to let the real part of Z_c be positive. Using eqns (17) and (18), Z_c and γ can be calculated from the measured impedances Z_1 and Z_1' and the impedances of a closed tube with depth L_0 and L_0',

$$Z_2 = -jZ_0 \cot(kL_0), \tag{19}$$

$$Z_2' = -jZ_0 \cot(kL_0'), \tag{20}$$

where k is the wave number of air. In order to obtain the characteristic impedance and the propagation constant, it is necessary to measure the acoustic impedance of two types for the air space depth behind the sample. A random signal was generated from the loudspeaker, and the transfer function H between the two microphones was measured using a two-channel FFT analyzer. The acoustic impedance of the material surface was obtained from

$$Z_1 = jZ_0 \frac{-H\sin(kL_x) + \sin[k(L_x + D_x)]}{H\cos(kL_x) - \cos[k(L_x + D_x)]}. \tag{21}$$

Using eqns (8) and (21), the sound absorption coefficient can be calculated.

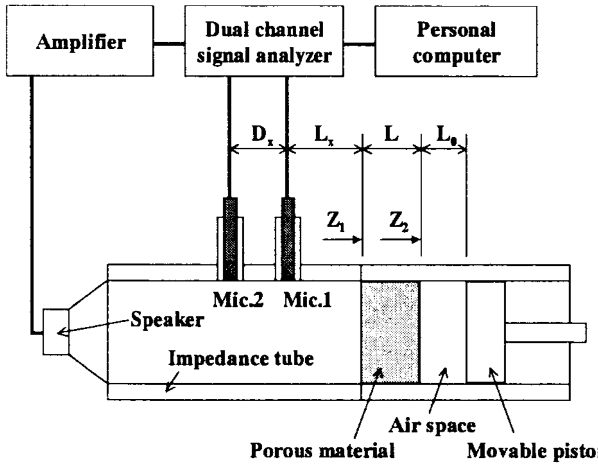

Figure 3: Block diagram of the impedance tube and the sample.

4 Experimental results and discussions

4.1 Bamboo fiber material

The bamboo fiber of 90-125 μm, 125-210 μm, and 210-425 μm fiber diameters was taken from breaking bamboo fibers with three kinds of mesh of differing roughness. The bamboo fiber was manufactured like felt with a binder to produce a cavity to exist inside the material. The sound absorption coefficient is measured

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according to the thickness, the air space depth, the apparent density and the bamboo fiber diameter of the material.

4.1.1 Thickness

The sound absorption coefficient for 25 mm, 50 mm, and 75 mm thick material is shown in Figure 4. The sound absorption coefficient increases in all frequency ranges as the thickness of the sample increases.

When there is air space depth inside and behind the material, the maximum value of the sound absorption coefficient moves from the high to the low frequency range. Therefore, sound absorption coefficient design is achieved by varying the air space depth and adjusting the maximum value with the sound absorption coefficient to the frequency.

4.1.2 Apparent density

The sound absorption coefficient for the material with apparent densities of 80 kg/m^3, 120 kg/m^3, and 160 kg/m^3 is shown in Figure 5. It was confirmed that the sound absorption coefficient increases in the middle and high frequency range as the density of the sample becomes higher. This is explained by the sound absorption principle of porous material that was described earlier in section 2.1. The number of the bamboo fiber increases per the unit area when the apparent density is large. When the energy loss increases as the surface friction increases, the sound absorption coefficient becomes high.

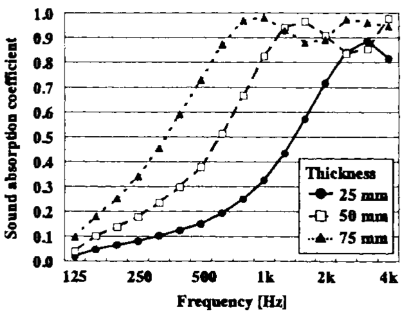

Figure 4: Sound absorption coefficient for 25-, 50-, and 75-mm thickness bamboo fiber backed by a rigid wall.

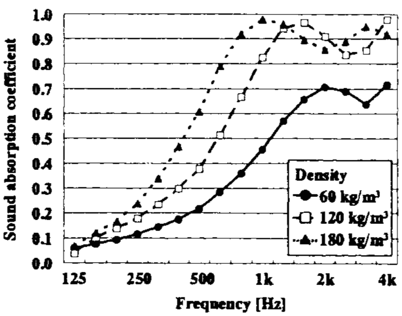

Figure 5: Sound absorption coefficient for 60-, 120-, and 180-kg/m^3 density bamboo fiber backed by a rigid wall.

4.1.3 Bamboo fiber diameter

The sound absorption coefficient for bamboo fiber diameters of 90-125μm, 125-210 μm, and 210-425 μm is shown in Figure 6. The sound absorption coefficient increases as the bamboo fiber diameter decreases. This phenomenon is explained by the sound absorption principle of porous material similar in section 4.1.2.

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4.2 Comparison of bamboo fiber material and glass wool

The acoustic characteristics of the material, the sound absorption coefficient, the characteristic impedance, and the propagation constant are shown in Figures 7- 9. The bamboo fiber material and the glass wool sample are similar as to both the characteristic impedance and the propagation constant. Therefore, bamboo fiber material has similar sound absorption characteristics to glass wool in the attenuation of the sound inside the material and the reflection in the material surface. It was confirmed that bamboo fiber material had enough sound absorption efficiency to qualify as sound absorbing material.

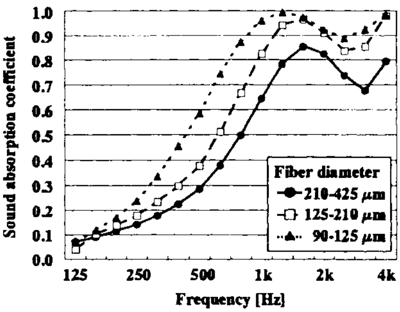

Figure 6: Sound absorption coefficient for 90-125, 125-210, and 210-425 μm fiber diameter bamboo fiber backed by a rigid wall.

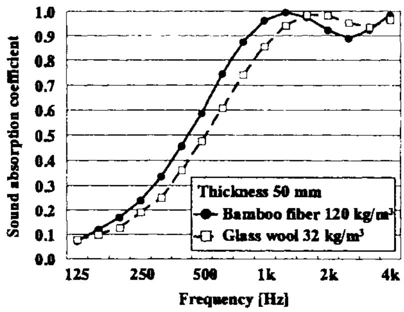

Figure 7: Comparison between bamboo fiber and glass wool.

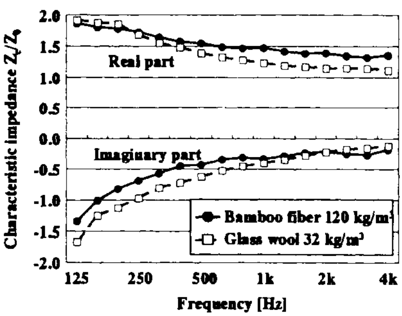

Figure 8: Comparison of characteristic impedance.

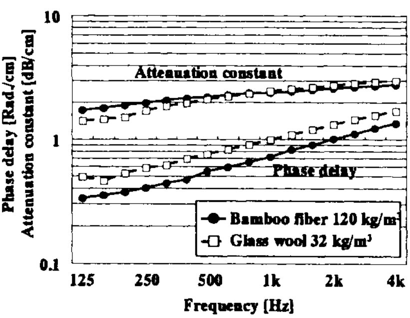

Figure 9: Comparison of propagation constant.

4.3 Combination of materials of different densities

The sound absorption coefficient effect can be improved by changing each parameter, and thus acoustic design becomes possible. However, because the

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thickness and the air space depth of the material are selected according to the actual design, it is difficult to make these quantities large. Therefore, in this study, we tried to find the best combination of samples of different densities for the improvement of sound absorption effects with the whole weight of the material constant. High density material on the side of the sound source was compared with material of uniform density, as is shown in Figure 10. It was confirmed that the acoustic characteristic of the material on the side of the sound source mainly influenced the sound absorption coefficient. Moreover, the sound absorption coefficient was computed from the theory formula of the sound absorbing material with multiple layers using the measured characteristic impedance and propagation constant. The combination of different densities in the frequency of 500<f<4000 Hz is shown in Figure 11. The contour lines of the sound absorption coefficient, pictured as the bamboo fiber material density on the side of the sound source (Layer 1) and the side of the rigid wall (Layer 2) show the y-axis and x-axis, respectively. The material thickness both was 25 mm. It was confirmed that the density of the material on the side of the rigid wall influences only the depth of the dip of the high frequency range, when the density of the sound source side is high. Arranging the material in the sound source side, improves the sound absorption coefficient with low frequency.

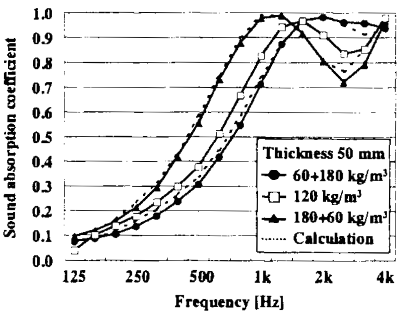

Figure 10: Sound absorption coefficient for combination of different densities of the bamboo fiber.

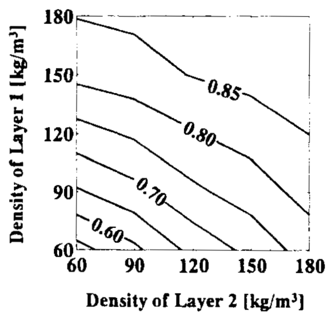

Figure 11: Optimization density of bamboo fiber layer. (500<f<4000 Hz)

4.4 Bamboo fiber board with high density

There is concern that the fiber scatters in bamboo fiber material. Therefore a fiberboard using the bamboo fiber as the surface material of the bamboo fiber material was made. The bamboo fiberboard was formed using 10% binders of material weight by hot press molding. A comparison of this bamboo fiberboard and plywood at the same density is shown in Figure 12. The sound absorption coefficient of the bamboo fiberboard is high in the high frequency range, because the bamboo fiberboard has both the characteristics of a board and cavities among

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the bamboo fiber. The sound absorption coefficient for different densities of the bamboo fiberboard is shown in Figure 13. When the density is greater, the sound absorption effect decreases with the high frequency range, because cavities among fibers are buried.

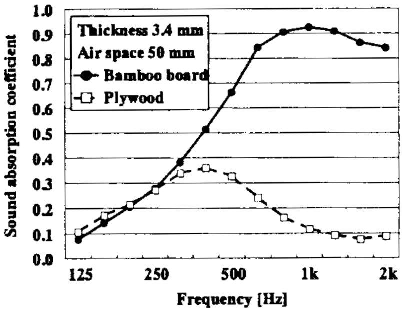

Figure 12: Comparison between bamboo fiberboard and plywood.

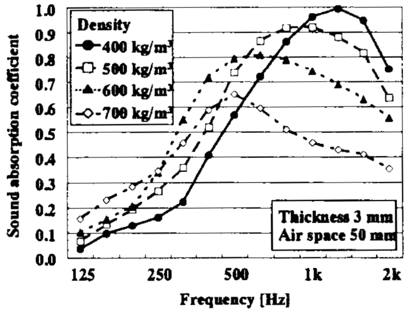

Figure 13: Sound absorption coefficient for different densities of the bamboo fiberboard.

4.5 Bamboo fiber board of resonance-type

The sound absorption structure of the resonance-type can obtain various characteristics by setting the board thickness, hole diameter, center length, and air space depth. Therefore, the acoustic characteristics of the resonance-type fiberboard are examined, as shown in Figure 14. The bamboo is higher than the resonance-type plywood in the high frequency range. A porous material of the bamboo fiber was then inserted behind the bamboo fiberboard (Figure 15), resulting in an increase in the characteristic of the resonance-type board. Thus, the bamboo fiberboard is more effective than the plywood when using it as the board and the resonance-type.

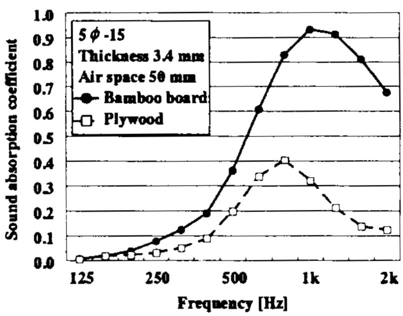

Figure 14: Comparison between resonance-type bamboo fiberboard and plywood.

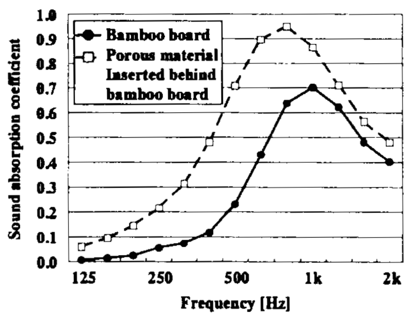

Figure 15: Bamboo fiber material (thickness 50mm) inserted behind the bamboo fiberboard.

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5 Conclusions

In this paper, alternative sound absorbing materials using bamboo fibers were developed. The performances of the bamboo fiber material and bamboo fiberboard were evaluated by measuring the normal incidence sound absorption coefficient. The following conclusions were drawn from this study.
(1) The bamboo fiber material possesses acoustic properties equivalent to those of glass wool.
(2) The sound absorption characteristic of bamboo fiber material can obtain various characteristics by setting the thickness, the air space depth, the apparent density, and the bamboo fiber diameter of the material.
(3) Fundamental design criteria was confirmed using the newly developed bamboo fiber material for the purpose of sound absorption.

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