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Sound Absorption and Mechanical Properties of Porous Stampable Sheet*



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1 Introduction

Fibrous materials such as glass wool and rock wool have so far been used as sound-absorbing materials in the construction and automotive industries. In recent years, as interest in residential and working environments has increased, the use of sound-absorbing materials has been expanding in the construction industry. In the automotive field also, sound-absorbing materials have been used in increasing amounts mainly around the engine and as interior parts to control the noise outside the car and to improve the feeling of quality in the car. All of these cases require materials that are superior to the conventional fibrous sound-absorbing materials in strength and moldability.

One way of obtaining sound-absorbing materials of excellent strength and moldability involves the molding of porous, stampable sheets, which are produced from glass fiber (GF) and polypropylene (PP) by the paper making process. Stampable sheets are the base material for molding and are ordinarily used to produce solid and strong parts. However, the stampable sheet manufactured by the paper making process expands in the direction of thickness and becomes porous when it is heated to above the melting point of PP. This characteristic, which is peculiar to the stampable sheet manufactured by the paper making process, can be utilized to produce porous mold[1]. Because porous molds thus obtained have excellent moldability and strength in spite of their lightness, they have been used in large quantities as lightweight interior materials for cars helping to reduce vehicle weight[1,2].

In porous mold, GF is dispersed to single fibers, and porous molds have fine pore structure similar to that of glass wool. As a result, porous molds have an excellent ability to absorb sound. With the stampable sheet manufactured by the conventional dry process, it is difficult to obtain porous molds that have such a fine pore structure, but the stampable sheet manufactured by the paper making process is especially suitable for obtaining sound-absorbing molded parts of high strength.

This paper presents the results of measurements of the sound absorption and strength of porous molds and describes the guideline for material design to ensure that these two properties are compatible with each other at higher levels. Furthermore, the paper describes other properties necessary for porous molds as sound-absorbing materials, such as resistance to water and freezing, and presents examples of application.

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2 Relationship between Flow Resistance and Sound Absorption

It has been reported that the sound absorption of porous materials is well correlated to the flow resistance of the materials[3]. Kinoshita[4] and Tatemichi et al.[5] analyzed the relationship between sound absorption and flow resistance in glass wool, metal wool, and other materials. Kinoshita reported that the maximum value of the sound absorption coefficient reaches the highest level in glass wool, etc. when the flow resistance is in the range of 400 to 500 Pa · s/m[4]. Miki reported an equation for the relationship between the flow resistance and sound absorption proposed by Delany-Bazley[6,7].

The GF content, porosity and thickness of porous molds have a great effect on sound absorption because they change the micro structure of the porous mold. The aforementioned flow resistance is employed to quantitatively demonstrate the relationship among the sound absorption property and the GF content, density and thickness of porous molds. The GF content used in this study is defined as the mass percentage of GF in the mass of sheet.

3 Experiment

3.1 Manufacturing Method of Porous Molds

The stampable "KP SHEET"[8] manufactured by the paper making process at K-Plasheet Corp. was molded in a porous state in the laboratory to obtain porous molds.

Because the GFs in the stampable sheet are fixed by PP in a compressed condition, the stresses stored in the GF are relieved when PP is melted by heating the sheet again, with the result that the sheet expands to the original web thickness. When the stampable sheet, which has expanded in the direction of thickness with PP in a molten state, is compressed to a prescribed clearance and cooled, a porous mold with lower density than the dense stampable sheet, is obtained.

In this experiment, a stampable sheet cut out into a square with sides of 230 mm was heated to 210°C by a heating press and expaned in the direction of thickness. It was then cooled in a cooling press that was set to clearances of 2–22 mm to obtain a sheet-like porous mold. The density and thickness of the porous mold can be controlled by web weight and the clearances during expansion processing.

3.2 Measurement of Sound Absorption Coefficients

(1) Measurement of Normal Incidence Sound Absorption Coefficient

The sound absorption property of samples was evaluated by the normal incidence sound absorption coefficient based on the tube method described in JIS A1405[9]. The equipment used to measure this coefficient was the "SG-3E" of RION Corp. The prescribed air gap was installed from the bottom of a sound tube whose one end was sealed, and a sample formed into a 91 mm disk was attached. Pure sounds of 100–3 150 Hz were generated within the sound tube and the maximum and minimum values ($L_{P\,max}$ and $L_{P\,min}$, respectively) of sound pressure level in the tube were recorded. The normal incidence sound absorption coefficient α was calculated from the obtained sound pressure levels using Eg. (1)

$$\alpha = 4/(n + n^{-1} + 2) \cdots\cdots (1)$$

where $n = \log^{-1}\{(L_{P\,max} - L_{P\,min})/20\}$

(2) Measuring Method of Reverberant Sound Absorption Coefficient

The sound absorbability of samples was evaluated by the reverberant sound absorption coefficient described in JIS A1409[9]. Both the reverberant time, T_1 without sample in the reverberant room and the reverberant time, T_0 with a sample in the reverberant room were measured, and the reverberant sound absorption coefficient α_{rev} was calculated using Eq. (2).

$$\alpha_{rev} = 0.163 \times V/\{(1/T_1 - 1/T_0) \times S\} \cdots\cdots (2)$$

where V: Volume of reverberant room, 450 m^3
S: Area of sample, 10 m^2

3.3 Measurement of Flow Resistivity

In the middle of a tube 50 mm in inside diameter was installed a disk-like sample with the same inside diameter as the tube. Care was taken so that air did not leak from the gap between the sample and the tube wall. After that, N_2 gas was flowed at a prescribed velocity, and the flow velocity and pressure drop were measured after the former became constant. The flow velocity and pressure drop are denoted by u and ΔP, respectively. The flow resistance R was obtained by substituting obtained u and ΔP into Eg. (3)

$$R = \Delta P/u \text{ (Pa} \cdot \text{s/m)} \cdots\cdots (3)$$

The specific flow resistance R_v at a flow velocity of 0 was extrapolated from the relationship between R and u. The value obtained by dividing R_v by the thickness of porous material was regarded as the specific flow resistivity R_s.

3.4 Evaluation of Compressive Strength

The compressive strength of porous molds and glass wool boards was evaluated as an example of strength in accordance with the compression test method of hard foam plastics described in JIS A7220. The glass wool boards with densities of 0.048 and 0.024 g/cm^3 (that is, normal sound-absorbing materials), which are included in the glass-wool boards described in JIS A 6306 were used. These porous molds and glass-wool boards were formed into disks with a diameter of 50 mm and a thickness of 50 mm to prepare test pieces. The test pieces were set as flat sheets and were then compressed using a disk-like compression jig with a diameter of 100 mm. The compressive strain ε and compressive strength σ were obtained from Eqs. (4) and (5).

$$\varepsilon = \delta / h \cdots\cdots (4)$$

$$\sigma = F/S \text{ (Pa)} \cdots\cdots (5)$$

where δ: Amount of displacement (cm)
h: Thickness before the test (cm)
F: Load (Pa $\cdot$ cm^2)
S: Area of test piece (cm^2)

Then, the compressive elastic modulus E in the initial elastic region was calculated from Eq. (6)

$$E = \Delta\sigma / \Delta\varepsilon \text{ (Pa/cm}^2) \cdots\cdots (6)$$

where $\Delta\sigma$: Change in strength between two points in the elastic region (Pa $\cdot$ cm^2)
$\Delta\varepsilon$: Change in strain between two points in the elastic region

3.5 Evaluation of Water Absorption and Drying Properties

The water absorption and drying properties of porous molds and glass-wool boards were evaluated by the following method. Square samples with sides of 100 mm were prepared. The sample thickness was 22 mm and 5 mm for porous molds and 25 mm for glass-wool boards. The samples were immersed in 500 mm of water depth so that the section faced upward. The samples were pulled out of the water at regular intervals and the mass was measured. After the increase in mass stopped, the samples were then put in a climate-controlled room maintained at a temperature of 23°C and a relative humidity of 50%, and put on stands made of wire netting. The mass of the samples was measured at regular intervals.

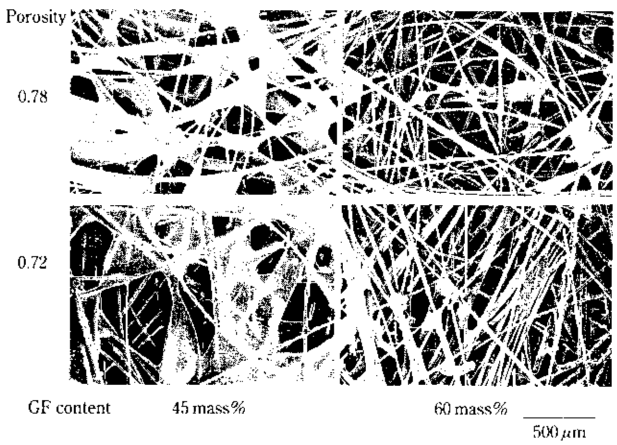

Photo 1 SEM micrographs of porous KP-sheet molded boards

Photo 2 SEM micrograph of porous KP-sheet molded boards

4 Results and Discussion

4.1 Pore Structure of Porous Molds

Photo 1 shows the SEM micrographs of porous molds with different GF content and porosity. When the GF content was 45 mass% and the porosity was 0.78, the pores made by GF were partially filled with PP. When the porosity was 0.72, still more pores were filled with PP. In contrast, the pores made by GF were finer at a GF content of 60 mass% than at 45 mass% and the pores were less filled with PP in both cases of 0.78 and 0.72 porosity. In other words, the higher the GF content, the finer the pore structure was and the less the pores were filled with PP.

Photo 2 shows an enlarged SEM micrograph of porous mold with GF content of 60 mass% and a porosity of 0.78. The PP in the porous mold is concentrated near the contact points of GF and bonds GF together. The PP in the porous mold apparently collected near the contact points of GF due to the surface tension of molten PP itself, when the dense stampable sheet expanded in the direction of thickness.

4.2 Normal Incidence Sound Absorption Coefficient of Porous Molds

An example of measurment of the normal incidence sound absorption coefficient of porous molds is shown in **Fig. 1**. In this figure, the data of two kinds of porous molds with different GF content were compared. In both cases, the sound absorption coefficient increased with

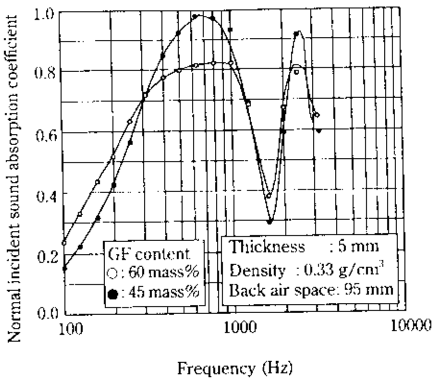

Fig. 1 Sound absorption characteristic of porous mold

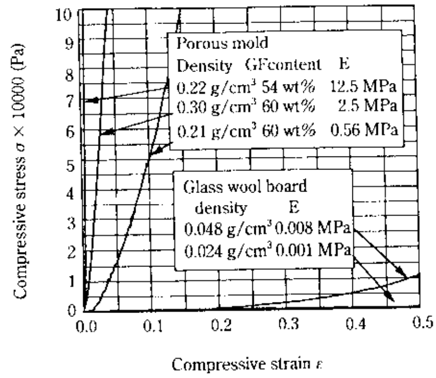

Fig. 2 Compressive strength of porpus molds and of glass wool boards

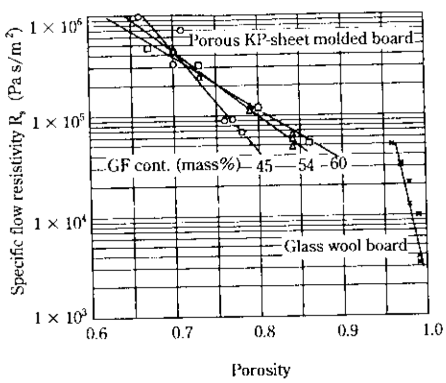

Fig. 3 Relationship between specific flow resistivity and porositiy for porous molds and for glass wool boards

increasing frequency and reached a maximum level at a certain frequency. The maximum value of sound absorption coefficient varied greatly depending on the GF content of porous molds. It has been ascertained that in addition to the GF content, the thickness and porosity of porous molds also have great effect on the maximum value of the sound absorption coefficient. In the examination of the sound absorption property that will be described later, the maximum value of the normal incidence sound absorption coefficient is used as the representative value of sound absorbability after the technique of Kinoshita et al.[4].

4.3 Compressive Strenght of Porous Molds

Figure 2 shows the compressive stress-strain curve and elastic modulus E of porous molds and glass-wool boards. When the GF content are equal, the higher the density, the higher σ will be. When the density are equal, the lower the GF content, the higher σ will be. A comparison between the elastic modulus of porous molds and glass-wool boards shows that E is higher porous molds in all cases.

The GF content of porous molds usually ranges from 45 to 70 mass%. In this range, strength decreases with increasing GF content. This is because PP, the binder of GF, decreases, causing the binding effect of PP at the contact points of GF to decrease. Furthermore, strength decreases because the number of internal pores increases with decreasing density of the porous mold.

4.4 Flow Resistivity of Porous Molds

The relationship between R_s and porosity of porous molds with different GF content is shown in **Fig. 3**. This figure shows a plot of previously measured values of glass-wool board for comparison[4]. Both in the porous molds and glass-wool board, R_s decreases with increasing porosity. In the porous molds, the slope decreases with increasing porosity. At porosity of 0.7 and more, R_s increases with increasing GF content even when the porosities are equal.

As mentioned earlier, the pore structure of porous molds is such that the higher the GF content, the finer pores will be and the lower the GF content, the more pores will be filled with PP. Therefore, R_s increases with increasing GF content when the porosity is high, whereas the lower the porosity the greater the effect of the filling of pores with PP. When the porosity is 0.7 or less, the lower the GF content (i.e., the higher the PP content), the larger R_s will be. Apparently as a consequence, the slope of the relationship between R_s and porosity changes depending on the GF content.

The reason why glass-wool boards that provide the same flow resistivity as porous molds have a higher porosity might be ascribed to the diameter of GF that is contained in both. Glass-wool boards are composed of GF with a diameter of about 6 μm, while porous molds are mainly composed of GF with diameters of 10 to 20 μm. When the porosity is constant, materials with a large fiber diameter have small R_s because of small specific surface area. It is therefore likely that because strength and other properties are improved by using GF with a larger fiber diameter than glass-wool boards, R_s

decreases at the same porosity.

4.5 Relationship between Flow Resistance and Normal Incidence Sound Absorption Coefficient of Porous Molds

Figure 4 shows the relationship between the maximum value of normal incidence sound absorption and the specific flow resistance R_v for a specific thickness. This figure also shows the results obtained from porous molds with different GF content, densities and thicknesses. The relationship between the maximum value of sound absorption coefficient and R_v can be expressed by one curve regardless of GF content, density and thickness. The maximum value of the sound absorption coefficient was obtained when R_v was 350–500 Pa · s/m and this value decreased remarkably when R_v was both higher and lower than this level.

The fact that the maximum value of sound absorption coefficient was obtained when R_v was 350–500 Pa · s/m almost completely agrees with the results reported by Kinoshita et al.[4]. It is possible that in porous molds with R_v higher than this range, sounds are reflected on the surface of the material and in its interior and hence are not thoroughly absorbed by the material, whereas at too low R_v, air friction is greatly reduced in pores when sounds pass through the material, with the result that sounds pass through the material without thorough absorption of their energy. Therefore, in order to use porous molds as sound-absorbing materials, it is necessary to determine each condition so that R_v is always in the range of 350–500 Pa · s/m when combinations of GF content, porosity and thickness are determined in consideration of strength and other properties.

Figure 5 shows an example of the normal incidence sound absorption coefficient of porous materials for which each condition was determined using this method. Each porous material has a high sound absorption coefficient. As described above, the selection of materials by flow resistance can provide a guideline in material design for the optimum design of sound absorbability by considering other required properties such as strength.

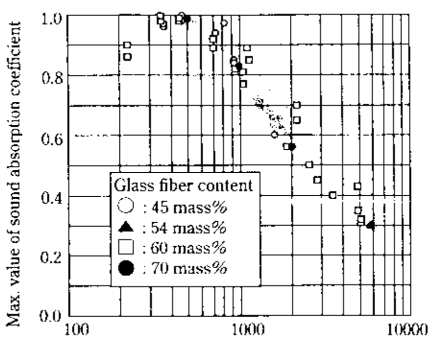

Fig. 4 Relationship between the maximum value of sound absorption coefficient and specific flow resistance for porous molds

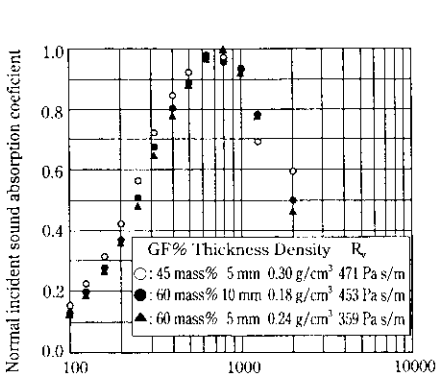

Fig. 5 Sound absorption characteristic of porous molds with 100 mm back-air space

5 Other Properties of Porous Molds

5.1 Comparison with the Reverberant Sound Absorption Coefficient of Glass Wool Boards

A comparison of sound absorbability was made between porous molds and glass-wool boards by the reverberant sound absorption coefficient. The thickness of the porous molds and glass-wool boards was 22 mm and 25 mm, respectively, and a 100 mm air gap was provided behind each material. The results of measurement are shown in **Fig. 6**. The porous molds and glass-wool boards, which had almost the same thickness, had the same sound absorbability in spite of their different densities.

5.2 Water Absorption/Drying, Freezing Resistance and Alkali Resistance

Figure 7 shows changes in mass in the water absorp-

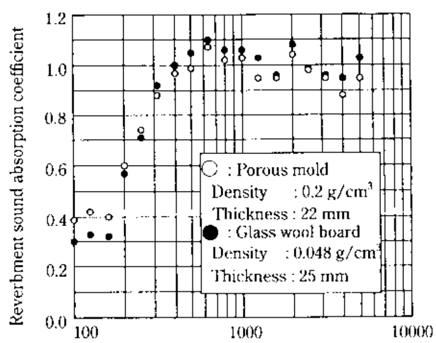

Fig. 6 Comparison of sound absorption characteristic between porous mold and glass wool board with 100 mm back-air space

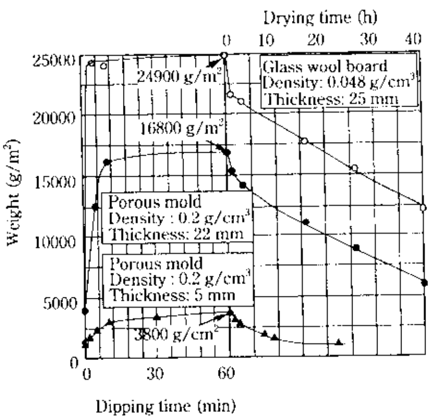

Fig. 7 Water absorption and drying time of porous molds and glass wool board

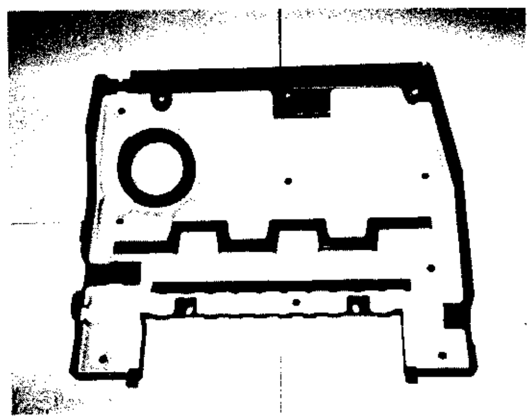

Photo 3 A mold of porous KP-sheet used for a sound insulator in engine room

tion/drying test of porous molds and glass-wool boards. Both the porous molds and the glass-wool boards showed an increase in weight when they were immersed in and subseguently absorbed water. The mass of glass-wool boards almost reached the saturation point within 5 min of immersion in water, while it took 10–20 min for the glass-wool boards to reach it. Furthermore, it was found that after thorough water absorption, the porous molds were lighter than the glass-wool boards and took less time for the sheet of porous mold to return to its original weight. This could be ascribed to the GF diameter, structure of the GF layer and surface treatment of the porous molds and glass-wool boards.

The alkali resistance of porous molds was then evaluated. Porous molds were immersed in an aqueous solution of 10 mass% sodium hydroxide for 7 d. The size was measured after drying. The change in length and breadth was 0.3% or less and the change in thickness was 0.7% or less.

Lastly, the freezing resistance of porous molds was evaluated by the testing method described in JIS A1435. A freezing/melting cycle at $-20°C$ and $+5°$ in a water-containing condition was repeated 20 times and changes in appearance, size and sound absorption were investigated, but there was no change in any of these properties.

PP, which is the binder of porous molds, absorbs water in a quantity of only about 1/10 of that absorbed by the phenol resin used in glass wool board, and is relatively stable in the presence of alkalis.

6 Examples of the Application of Porous Molds as Sound Absorbing Materials

Examples of the application of porous molds are described below. **Photo 3** shows an example in which a porous mold was used as the sound insulator in the engine cover of an automobile. The stampable sheet manufactured by the paper making process is molded into a porous mold of a complex concavo-convex shape and installed in the interior of engine cover with a self-maintaining air gap.

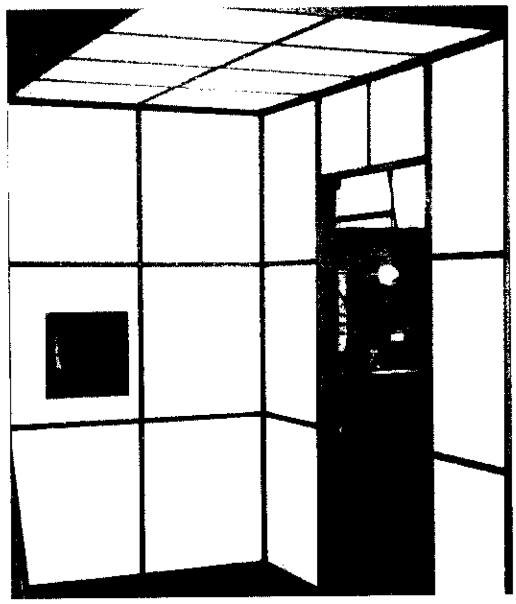

Photo 4 Appearance of porous KP-sheet used for a sound insulator in factory

In addition to the engine cover, the sound absorption property of roof trim board that accounts for a large amount of the car interior materials is attracting attention. Because porous molds have excellent in sound absorbability and strength and are light in weight and highly moldable, their practical application as acoustic car roof trim boards in passenger cars and trucks is being examined.

Photo 4 shows an example in which a sheet-shaped porous molds were used as a sound insulator on the wall of machine room. Porous mold does not need some kind of reinforcement or treatment on their surface because of their sufficient mechanical and water-proof propertis.

7 Conclusion

(1) Porous molds, which are produced by expansion molding of stampable sheets manufactured by the paper making process, have excellent properties of strength, resistance to deformation and sound absorption.

(2) The sound absorption and strength properties of porous molds depend on the GF content, porosity and thickness. The sound absorption property is well correlated to flow resistance. Porous molds show an excellent sound absorbability when the combinations of GF content, porosity and thickness are determined so that the flow resistance falls in the range of 350–500 Pa · s/m.

(3) Porous molds that are optimally designed for sound absorption can absorb sound as effectively as glass-wool boards, and provide higher strength, water resistance, alkali resistance and freezing resistance than glass-wool boards.

(4) It is expected that porous molds will be used in an increasing number of applications in fields such as the automobile and construction industries.

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