Cell Distributions in and Sound Absorption Characteristics of Flexible Polyurethane Foams

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ABSTRACT: In this article, the two-dimensional distributions of cells from the cross section of some flexible polyurethane foams were cleared, and the three-dimensional distributions of cells based on Saltykov's theory were estimated further. As a result, it was found that a mean of the two-dimensional distributions of cells was a good linear relation with a mean of the three-dimensional distributions of cells, and it was confirmed that cell structure of the foams which should have been analyzed in the three-dimensional distributions was evaluated by analysis of the two-dimensional distributions fully. It was also found that not only cell number but also cell distribution was necessary in the evaluation of flexible polyurethane foams, and cell diameter was closely related to the sound absorption coefficient in polyester-based flexible polyurethane foams. © 1997 John Wiley & Sons, Inc. J Appl Polym Sci **65:** 1395–1402, 1997

Key words: cell; flexible polyurethane foam; plastic foam; Saltykov's theory; cell number; quantitative microscopy

INTRODUCTION

There are rigid and flexible polyurethane foam in polyurethane foams; the former are used as heat insulators for closed-cell foams, and the latter as acoustic materials, cushion materials, car interior decoration materials, and buffer materials for open-cell foams.

The physical properties of foamed substances are decided by kind of material, foamed magnification, and cell structure. Cell structure is related to shape of cells, size of cells, and continuity of cells in a complicated way. Theoretical investigation of cell structure is useful in gaining an essential understanding of the physical properties of plastic foams, and is important for quality control and investigation of practical characteristics.[1–6]

Fujino and others[7] supposed that some minimum units of foaming medicine which disperse in a plastic at random gather and form one cell; they then analyzed the distributions of cell size theoretically. In the case of spherical cells in closed-cell plastic foams, Mihira and others[8] analyzed relations between the radius distribution of spheres and the radius distribution of circles given on the section cut two-dimensionally by applying the method of probability and statistics. Kadokura and Kuroe[9] concluded that a relation between cell structure and sound absorption properties was approximately accounted for by flow resistance.

Young's modulus of flexible polyurethane foams was predicted by the finite element method (FEM) that used a simple hexagon model,[10] but Young's modulus should examine cell structure from observation of the cell's shape, diameter, and porosity of the section of foams. In this article, two-dimensional distributions of cell diameters from each section were revealed, and a method to analyze the three-dimensional distributions of cell diameters was examined in some flexible polyurethane foams.[11,12] Cell number and sound absorption coefficients were estimated.[13]

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Table I Physical Properties of Samples

Sample Number	Cell Number	Tensile Strength (MPa)	Elongation (%)	Porosity
1	22	0.98	144	0.956
2	37	1.75	220	0.961
3	62	1.34	148	0.926
4	41	0.99	336	0.984
5	37	0.98	150	0.979
6	41	1.37	122	0.966
7	48	1.68	246	0.967
8	40	1.17	142	0.972

EXPERIMENTAL

In the production of polyurethane foam, polyurethane created by the reaction between polyol and isocyanate is foamed by utilizing the carbon dioxide caused by the reaction between isocyanate and water. Table I summarizes the properties of samples, which are flexible polyurethane foams made by the Inoac corporation; samples 1–3 are oil-resistant polyester-based flexible polyurethane foams, and samples 4–8 are polyether-based flexible polyurethane foams. Hardness and resilient moduli are based on JIS (Japanese Industrial Standard) K 6401-1980, Flexible Urethane Foam for Cushion. A small piece of the flexible polyurethane foam was buried in the polyester resin of the two-liquid type made by the Malto corporation, vacuum pumped, and hardened at 60°C for 24 h. Figure 1 shows a microphotograph of the mask after sandpaper polishing and abrasion buffing. A section of the cell is nearly hexagonal, and a section of the skeleton is nearly triangular. One has a thin membrane among these skeletons, and the other has not. From the place where there is not a thin membrane, the air enters the inside of the cell, and the sound absorption's effect appears by friction. It does not appear in hard polyurethane foams because of the thin membrane's existence among these skeletons.

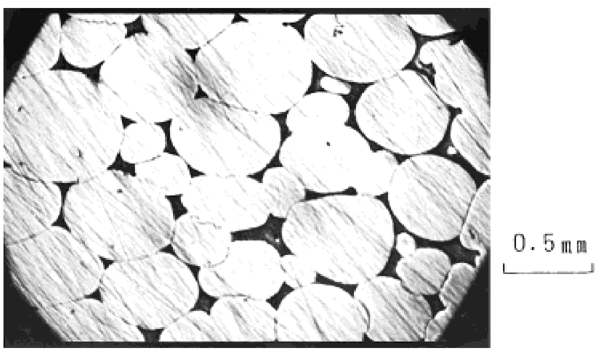

Figure 1 A section of the flexible polyurethane foam made by Inoac corporation.

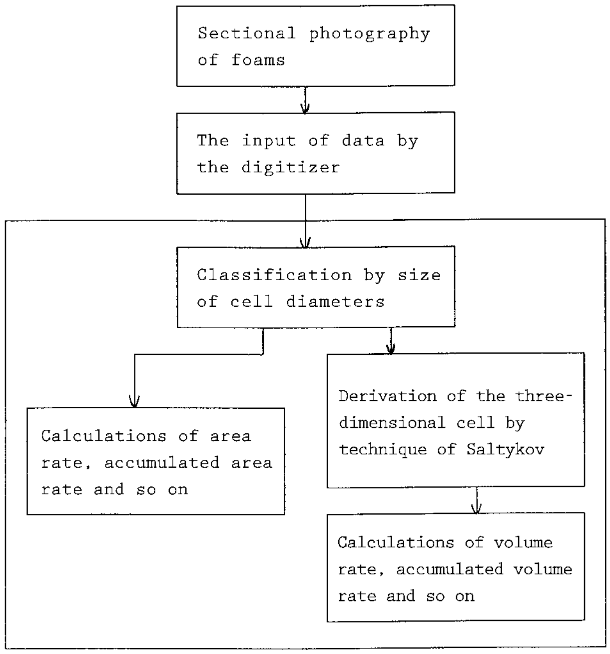

Figure 2 Flow of analysis method.

The cell number is the number of cells in a 1-in. cross section. Porosity ν is derived from foam density and urethane density of the solid part.

$$\nu = 1 - \rho_0/\rho$$

Where ρ_0 is the foam density and ρ is the urethane density of the solid part.

ANALYSIS

Figure 2 shows the flow of analysis method. After filming a section of the foam, the coordinates were input along the circumference of the cell by a digitizer, the area of the cell calculated, and cell diameter being led from the cell regarded as a circle. The cell's size was classified by personal computer in 0.15-mm-diameter intervals, and the cell size distribution was revealed. It was defined that fractional area was the ratio that divided a total of cell area between each ward by cell area of the whole, and accumulated fractional area was the total of each fractional area which accumulated from small wards of cell diameter. Furthermore, fractional area distributions and accumulated fractional area distributions from the area of each

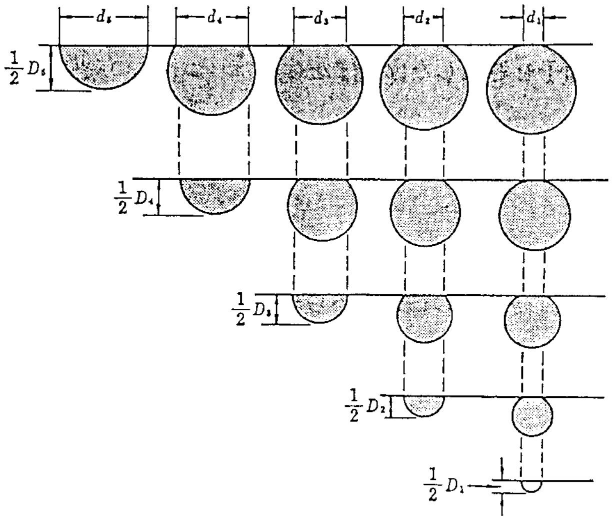

Figure 3 Relation between sections with diameters d_1 to d_5 and globes producing their diameters.[14]

cell were calculated. On the other hand, the three-dimensional cell number distribution was led from the two-dimensional cell size distribution derived by Saltykov's technique,[14] and the fractional volume distribution and accumulated fractional volume distribution were calculated. Here, fractional volume and accumulated fractional volume were defined similar to fractional area and accumulated fractional area.

Saltykov's technique is explained here. Figure 3 shows in the plane state that the circle of diameters from d_1 to d_5 appears when the globe of five sizes is cut off. $N_A(1)$, which is the circle's number of d_1 class diameter, is the total from $N_A(1, 1)$ to $N_A(1, 5)$. $N_A(1, 5)$ is the circle's number of d_1 class diameter by the globe of diameter D_5 here. $N_A(2)$, $N_A(3)$, $N_A(4)$, and $N_A(5)$ are similar.

$$
\begin{aligned}
N_A(1) &= N_A(1, 1) + N_A(1, 2) + \cdots + N_A(1, 5)\\
N_A(2) &= N_A(2, 2) + \cdots + N_A(2, 5)\\
N_A(3) &= N_A(3, 3) + \cdots + N_A(3, 5)\\
N_A(4) &= N_A(4, 4) + N_A(4, 5)\\
N_A(5) &= N_A(5, 5)
\end{aligned}
$$

$N_A(i)$ is the circle's number of diameter d_i class $(d_{i-1} \sim d_i)$ measured on the observed side. $N_A(i,j)$ is the circle's number of diameter d_i class by the globe of diameter D_j.

Figure 4 shows the way to form the cutting circle of d_i class diameter in diameter D_j. Probability p, a random plane, crosses between h_{i-1} and h_i in a globe of diameter D_j that is equal to the divided thickness of the circle's foil h by particle radius $D_j/2$.

$$P = \frac{h}{D_j/2} = \frac{h_{i-1} - h_i}{D_j/2}$$

In the case of counting only a section of one specified size d_i, it follows that the number of the section observed in unit area is related to the globe's number of diameter D_j unit volume, $N_V(j)$.

$$N_V(j) = \frac{N_A(i,j)}{p} \cdot \frac{1}{D_j} = \frac{N_A(i,j)}{2(h_{i-1} - h_i)}$$

Where $h_i = (D_j^2 - d_i^2)^{1/2}/2$, and $N_A(i,j) = \{(D_j^2 - d_{i-1}^2)^{1/2} - (D_j^2 - d_i^2)^{1/2}\} \cdot N_V(j)$. When the interval of the classes is equal, and it is Δ, and $d_1 = \Delta$, $d_2 = 2\Delta$, $d_{i-1} = (i-1)\Delta$, $d_i = i\Delta$, $D_j = j\Delta$, and $(D_j^2 - d_{i-1}^2)^{1/2} - (D_j^2 - d_i^2)^{1/2} = a_{ij}$,

$$a_{ij} = \Delta[\{j^2 - (i-1)^2\}^{1/2} - (j^2 - i^2)^{1/2}]$$

Accordingly, from the probability that a globe forms cutting circles, and the number appeared as sectional circles of d_i class, and so on, relations between the number of the circle on the section and the number of the globe in space is revealed.

$$
\begin{aligned}
N_A(1) &= a_{11}N_V(1) + a_{12}N_V(2) + \cdots + a_{1n}N_V(n)\\
N_A(2) &= a_{22}N_V(2) + \cdots + a_{2n}N_V(n)\\
&\cdots\cdots\\
N_A(j) &= a_{jj}N_V(j) + \cdots + a_{jn}N_V(n)\\
&\cdots\cdots\\
N_A(n) &= a_{nn}N_V(n)
\end{aligned}
$$

As $N_A(j)$ is calculated from the measurement data on the foam's section, the distribution of a globe in space is given by solving this coalition linear equation about $N_V(j)$.

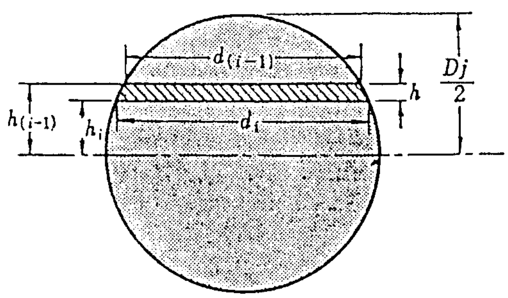

Figure 4 Acquisition of a circle of d_i class diameter from a globe of diameter D_j.[14]

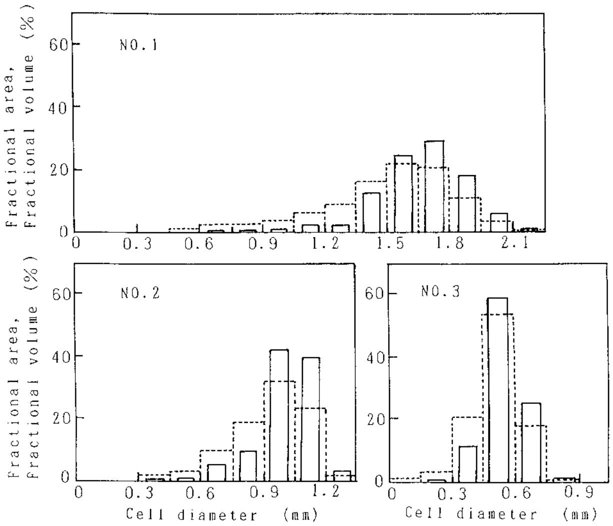

Figure 5 Comparison of fractional area and fractional volume distributions. (---) fractional area; (——) fractional volume.

RESULTS AND DISCUSSION

Cell Distributions

From the comparison of the cell number distributions of foams from sample No. 1 to sample No. 8, there is the difference among sizes of one flexible polyurethane foam, and there is the difference among kinds of foams. Figure 5 shows the fractional area distributions and the fractional volume distributions in No. 1, No. 2, and No. 3 of polyester-based flexible polyurethane foams, but there is individuality in each distribution, and the peak moves to the large side of cell diameters as for No. 1 and No. 2, and in addition to the sharpness of the peak, the distribution range of the cells is narrow as for No. 3, and the distribution range of the cells is as wide as for No. 1. The fractional volume distribution moves a little to the large side of the cell diameters as compared with the fractional area generally, but the peak of No. 1 moves to the large side of cell diameters, and the peaks of No. 2 and No. 3 almost agree. Figure 6 shows the fractional area distributions and the fractional volume distributions from No. 4 to No. 8 of polyether-based flexible polyurethane foams. The peak of No. 7 is sharp comparatively, but it has similar triangular distribution generally, and the peak of the fractional volume distribution is the diameter similar to the fractional area distribution, but on the whole it moved a little to the large side of cell diameters.

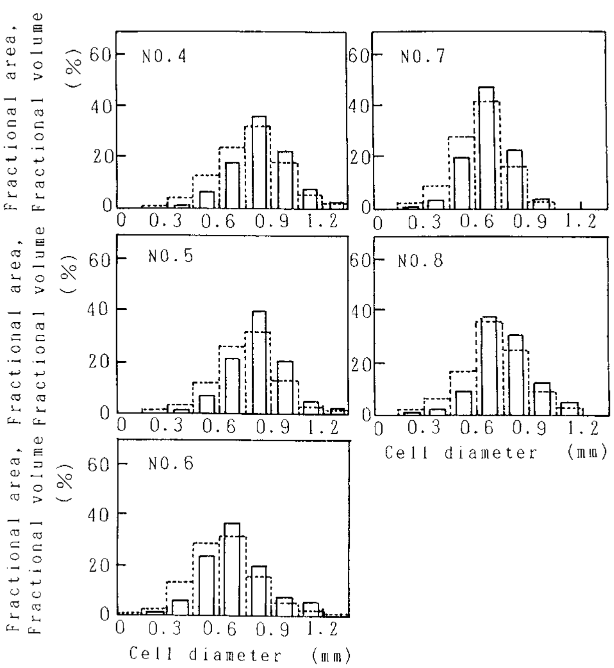

Figure 6 Comparison of fractional area and fractional volume distributions. (---) fractional area; (——) fractional volume.

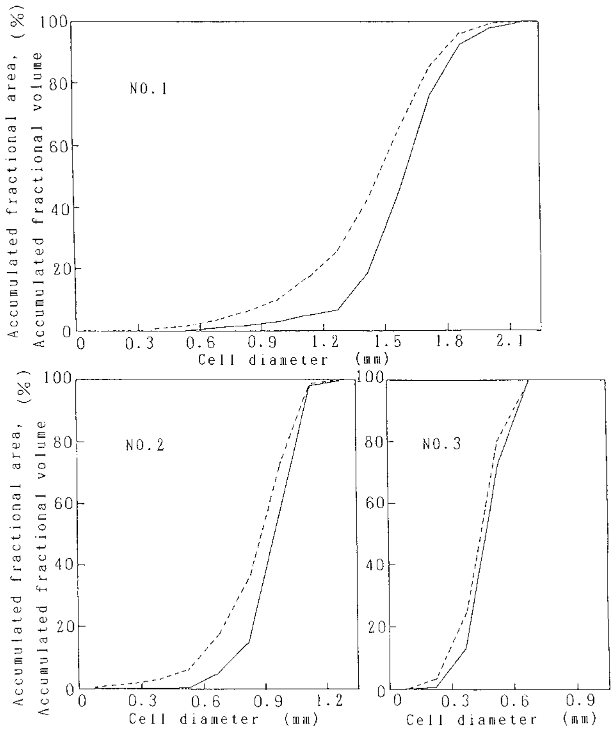

Figure 7 Comparison of accumulated fractional area and accumulated fractional volume distributions. (---) accumulated fractional area; (——) accumulated fractional volume.

Figure 7 shows the accumulated fractional area distributions and the accumulated fractional volume distributions of cell diameters in foams of No.

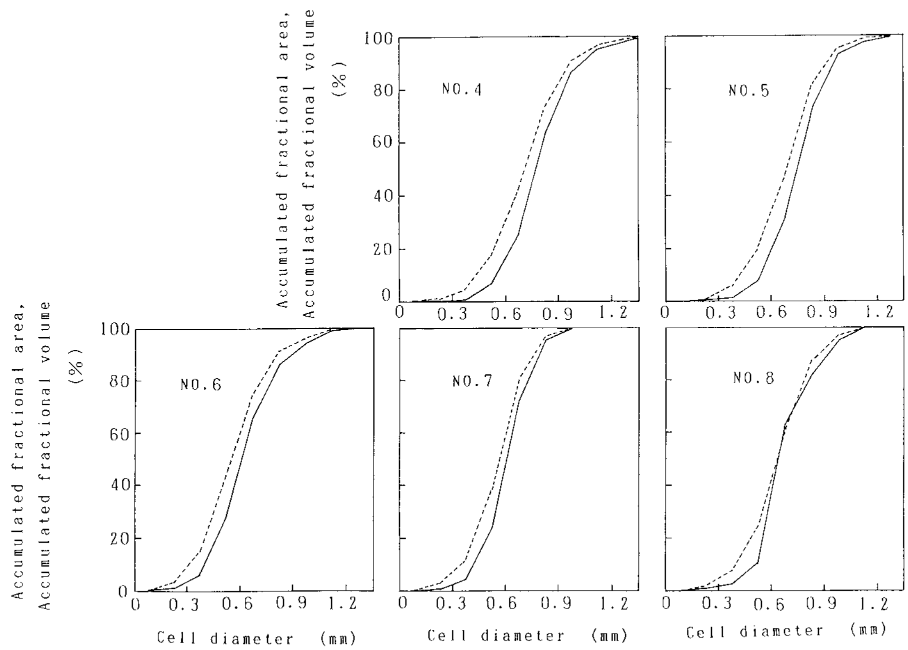

Figure 8 Comparison of accumulated fractional area and accumulated fractional volume distributions. (---) accumulated fractional area; (——) accumulated fractional volume.

1, No. 2, and No. 3. The accumulated fractional volume distributions is moving more to the large side of cell diameters than the accumulated fractional area distributions on the whole, and a difference between No. 1, No. 2, and No. 3 is large over the large part of cell diameters. Figure 8 is the accumulated fractional area distributions and the accumulated fractional volume distributions of cell diameters in foams from No. 4 to No. 8. The distributions from No. 4 to No. 8 show a tendency similar to No. 3. From now on, as for No. 1 and No. 8, in which the fractional area distribution and the fractional volume distribution were different from each other, a difference between the accumulated fractional area distributions and the accumulated fractional volume distributions is large, and over the large area of cell diameters, there is an individual movement.

Cell Diameter and Cell Number

It is defined that two-dimensional average cell diameter is the average of cell diameters picked, and area average cell diameter is the diameter led from the average area of one cell divided by the total of the area of cells by the total of the cell's number, and fractional area median is the cell diameter when the value accumulated from the small side of area cell diameters becomes 50%. Three-dimensional cell diameters are similar. It is indicated that all foam is in order of size, the two-dimensional average cell diameter, the area average cell diameter, and the fractional area median, and there is the difference of 0.2 mm at maximum between them. They are similar in the case of the three dimensions. Figure 9 shows a relation with the three-dimensional average cell diameter and the two-dimensional average cell diameter. Figure 10 shows a relation with the volume average cell diameter and the area average cell diameter. Figure 11 shows a relation with the fractional volume median and the fractional area median. There is a straight line relation in Figures 9–11, and in particular, there is a good straight line relation with the fractional volume median and the fractional area median.

Figure 12 shows a relation with the cell number and the fractional area median, the fractional volume median. The fractional volume median is ~ 0.05 mm larger than the fractional area median on the whole. It is supposed that there is a straight relation of the right backing away with the cell number and the cell diameter generally, but there is a lot of scattering in Figure 12. As for No. 1, which was the largest cell diameter, a difference between the fractional volume median and the fractional area median is large. As for No. 3, which has the smallest cell diameter, a difference between the fractional volume median and the fractional area median is small. Similarly to No. 4 and

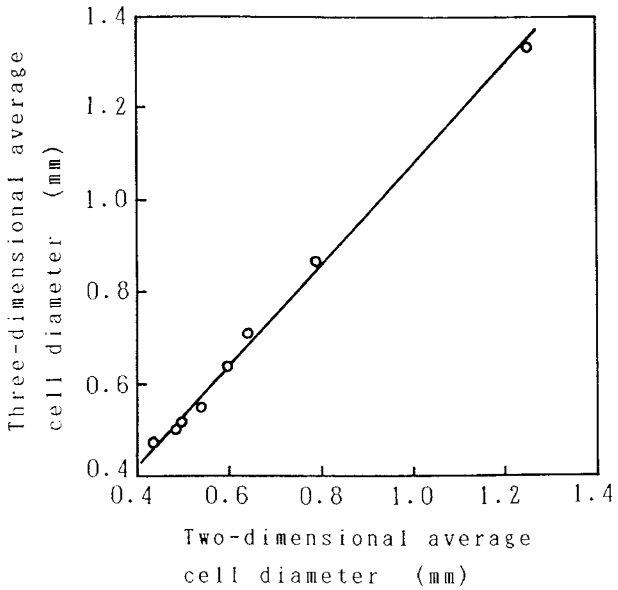

Figure 9 Relation between the average diameter of the two-dimensional cells and the average diameter of the three-dimensional cells.

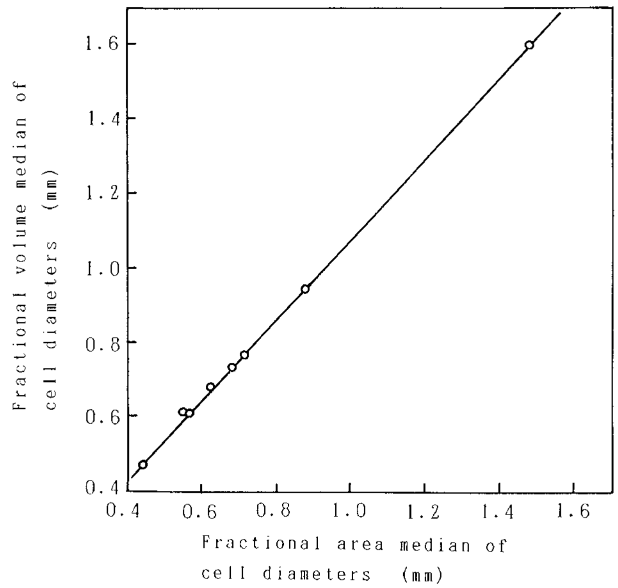

Figure 11 Relation between the fractional volume median and the fractional area median of cell diameters.

No. 6, No. 2 and No. 5 have equal cell numbers, but there is the different cell diameter. Accordingly, other than cell number, which is much employed in quality control, the average cell diameter derived from the cell distributions is important.

Sound Absorption Characteristics

Figure 13 shows relations between the normal incidence sound absorption coefficient and the frequency in polyester-based flexible polyurethane foams. The sound absorption coefficient of No. 2 and No. 3 is greatly larger in 250–2000 Hz than that of No. 1. From the cell distributions in Figure 5, the cell diameters of No. 1 are distributed over a larger cell range than that of No. 2 and No. 3. Therefore it is probable that the cell diameter has an influence on the sound absorption coefficient.

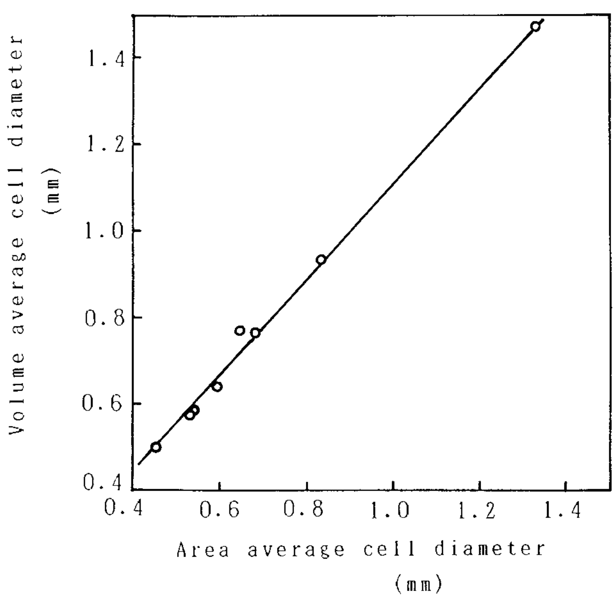

Figure 10 Relation between the average diameter of the cell's area and the average diameter of the cell's volume.

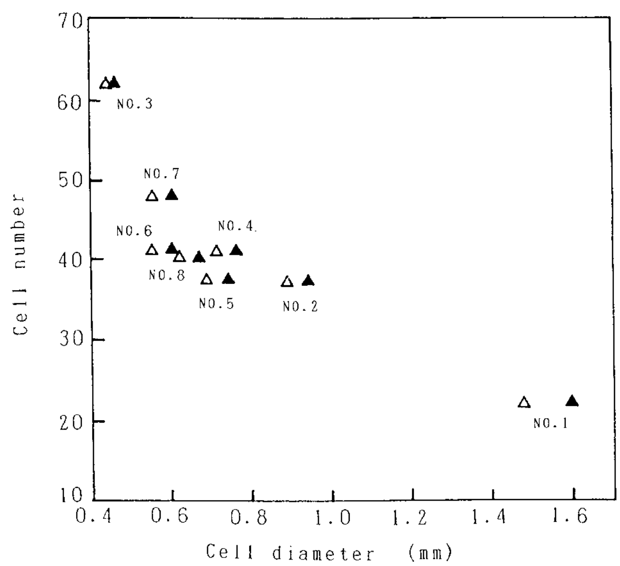

Figure 12 Relation between the cell number and the cell diameter derived as the fractional area median and the fractional volume median. (△) fractional area median; (▲) fractional volume median.

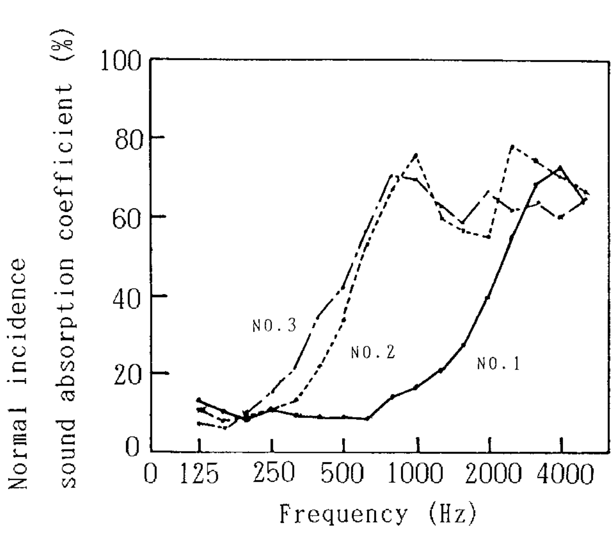

Figure 13 Sound absorption characteristics of polyester-based flexible polyurethane foams.

Figure 14 shows relations between the normal incidence sound absorption coefficient and the frequency in polyether-based flexible polyurethane foams. The polyether-based flexible polyurethane foams of No. 4–No. 8 show the sound absorption characteristics similar to that of No. 1. This difference of cell diameters between No. 1 and No. 4–No. 8 results in a probability that the stiffness of the solid part is related to the sound absorption coefficient. The sound absorption coefficient is found to be dependent on flow resistance. However, it has been not revealed that the sound absorption coefficient is related to microstructures.

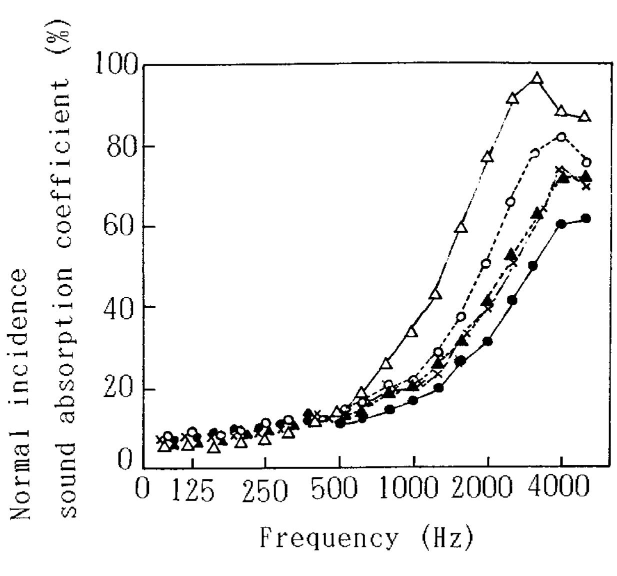

Figure 14 Sound absorption characteristics of polyether-based flexible polyurethane foams. (○) No. 4; (●) No. 5; (△) No. 6; (▲) No. 7; (×) No. 8.

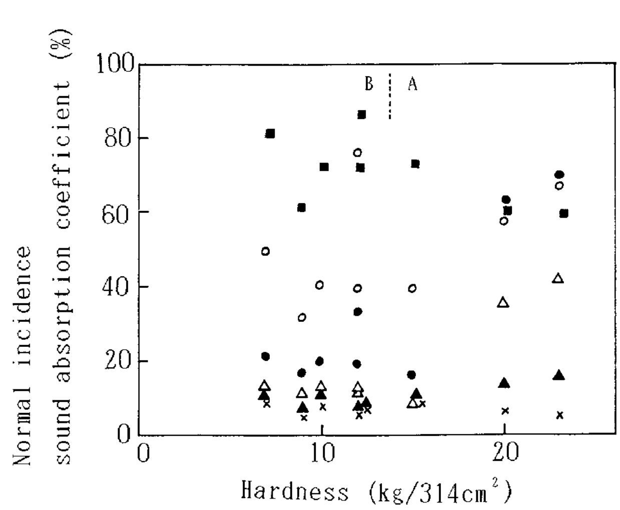

Figure 15 Relation between the absorption coefficient and the hardness. (A) polyester-based flexible polyurethane foams; (B) polyether-based flexible polyurethane foams. (■) 4000 Hz; (○) 2000 Hz; (●) 1000 Hz; (△) 500 Hz; (▲) 250 Hz; (×) 125 Hz.

Accordingly, it is necessary that mechanical properties of stiffness and so on are examined so as to make a clear sound absorption mechanism. Figure 15 shows a relation between the normal incident sound absorption coefficient and the hardness. Figure 16 shows a relation between the normal incident sound absorption coefficient and the resilient modulus. The sound absorption coefficient at 125 Hz and 250 Hz does not almost change with the hardness or the resilient modu-

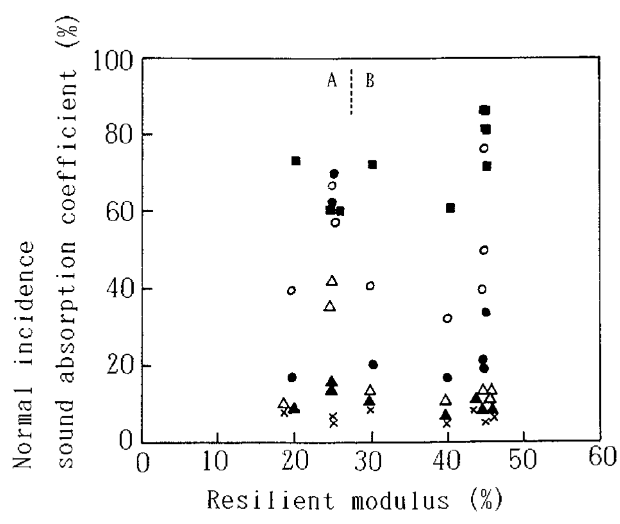

Figure 16 Relation between the absorption coefficient and the resilient modulus. (A) polyester-based flexible polyurethane foams; (B) polyether-based flexible polyurethane foams. (■) 4000 Hz; (○) 2000 Hz; (●) 1000 Hz; (△) 500 Hz; (▲) 250 Hz; (×) 125 Hz.

lus. On the other hand, the sound absorption coefficient at 500–4000 Hz changes with the hardness or the resilient modulus, but it is probable that the former is not related to the latter. The loss tangent tan δ was measured at normal temperature by a viscoelastic measuring machine in compression mode, with a frequency of 1–200 Hz and 50 μm displacement. The value is near to 0.15 in all foams, and so the sound absorption coefficient does not affect the loss tangent in their foams.

CONCLUSIONS

The coordinates of the cell's shape were inputted into a personal computer by digitizer from the sectional photograph of flexible polyurethane foams, the two-dimensional distributions of cells were led, and the three-dimensional distributions of cells were estimated on the base of Saltykov's theory. Both the two-dimensional distributions of cells and the three-dimensional distributions of cells had a curve of similar distribution, but the curve of the three-dimensional distributions moved to the large side of the cell diameters a little, and a mean of three-dimensional cells was larger than a mean of two-dimensional cells. A mean of two-dimensional cells was a good straight line relation with a mean of three-dimensional cells, and a relation between the fractional area median and the fractional volume median was good in particular. As a result, the sectional observation of foams should be essentially analyzed by the three-dimensional distributions, but analysis of the two-dimensional distributions can be effective as the subject of consideration. It was concluded that not only cell number but also cell distribution was necessary in the evaluation of flexible polyurethane foams. Still more, it was confirmed that cell diameter was closely related to sound absorption coefficient in polyester-based flexible polyurethane foams.

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