A Study of Composite Foams for Diving Suits Subjected to High Hydrostatic Pressure

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Synopsis

In order to obtain foams possessing flexibility and at the same time heat insulation under high hydrostatic pressure, composite foams with spherical rigid foams filled in flexible rubber foam at certain intervals were prepared and their thermal conductivity and flexural rigidity were studied. The following points were found: (1) With a unit model having a spherical rigid foam in the middle, the thermal conduction of a composite foam was analyzed under the conditions of steady one-dimensional heat flow. Theoretical equations giving overall coefficients of heat transmission under atmospheric and hydrostatic pressures were obtained, and the adequacy of these theoretical equations was confirmed by the measurement of overall coefficients of heat transmission of composite foams in an apparatus so constructed as to allow heat conduction experiments under pressures ranging from atmospheric to the hydrostatic pressure corresponding to 100-m depth in water. (2) The effect of the filled spherical rigid foams on heat insulation is notable under hydrostatic pressures corresponding to a 20-m depth or more in water. Under the hydrostatic pressure corresponding to a 100-m depth in water, the coefficient of heat insulation of the most closely filled composite foam used in the experiment was approximately 35% larger than that of the unfilled foam, while the theoretical most closely filled composite foam gives an approximately 110% increase. (3) Under the hydrostatic pressure corresponding to a 100-m depth in water, the flexural rigidity of the most closely filled composite foam used in the experiment was approximately one half that of an unfilled foam of the same heat insulating property.

INTRODUCTION

As resources on land are becoming scarce, the development of resources in the ocean have attracted more and more attention in recent years. Accordingly, much efforts have been made to bring diving work in water as deep as 100 m or so to daily activity. One of the important matters concerning diving work is the heat insulation of diving suits under high hydrostatic pressure. Diving suits must have high heat-insulating capacity, and at the same time they must be sufficiently flexible so as not to restrict body movement. Accordingly, the main materials used for diving suits have been flexible rubber foams with closed cells. However, the heat-insulating property of these flexible rubber foams decreases greatly under hydrostatic pressure as they undergo compression deformation very easily. According to the study by Ohno et al.[1] on a large number of foams used for commercial diving suits, the heat insulation decreases to approximately one half in a water depth of 10 m and to approximately one third in a water depth of 20 m.

In this report, we have carried out a study on composite foams of a double structure consisting of flexible and rigid foams, capable of fulfilling the two contradictory requirements, i.e., maintenance of heat insulation and flexibility under hydrostatic pressures upto a water depth of 100 m. We have derived

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theoretical equations which allow us to predict the heat conduction property of composite foams under hydrostatic pressure, and we have proved the adequacy of the equations by conducting heat conduction experiments for composite foams in an apparatus constructed for such experiments under hydrostatic pressures up to a water depth of 100 m. We thus studied the possibility of improving the heat insulation of diving suits under high hydrostatic pressure.

THEORY

Structure of Composite Foam

As described above, the use of a single-component foam cannot embody both sufficient flexibility and high heat-insulating property under high hydrostatic pressure. This is because a foam must have both low compressive and tensile moduli to be flexible, and the heat-insulating property of such a foam will decrease notably under hydrostatic pressure as its thickness decreases easily, and the volume fraction of gas phase, contributing greatly to heat insulation, also decreases owing to compression. Thus, as a heat insulation material possessing these contradictory properties, a foam of composite construction as shown in Figure 1 was conceived. The composite foam is composed of a flexible foam (like a rubber foam) as a matrix and of spherical rigid foams (whose diameters are somewhat smaller than the thickness of the matrix foam) as fillers placed in a square arrangement. When a hydrostatic pressure is applied to a foam of such a construction, the flexible matrix foam is compressed, but the spherical rigid foams are compressed very little. Thus, the composite foam, as a whole, will maintain its heat-insulating property to a certain extent. On the other hand, as the rigid foams are not composed of a single continuous phase, bending deformation can be a response of the matrix foam. Thus, the composite foam is expected to have a certain flexibility. The shape of the rigid foams to be filled can also be cylindrical or cubic. However, when it is considered that the matrix foam subjected to bending deformation will receive larger compression and tensile strains in sections further away from the neutral axis, spherical rigid foams will be most suitable.

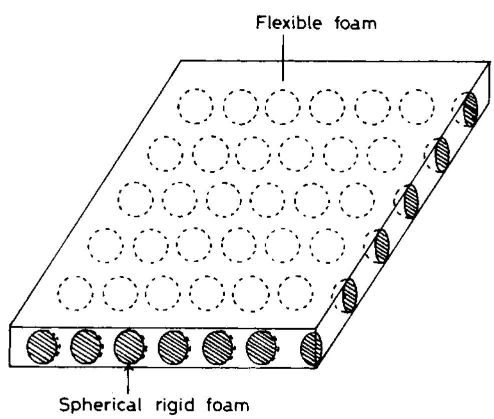

Fig. 1. Schematic diagram of composite foam filled with spherical rigid foams.

Overall Coefficient of Heat Transmission of Composite Foam

Heat insulation of materials is generally evaluated in terms of their thermal conductivity, the determination of which must be done with the thickness of the materials specified precisely. In the case of the composite foam studied in this work, it is difficult to specify the thickness of the foam precisely as the composite foam contains spherical rigid foams of a diameter close to its thickness, and thus the composite foam will have an uneven surface when compressed by hydrostatic pressure. Furthermore, when the gas phase is compressed under hydrostatic pressure, the thermal conductivity of the foam increases, and at the same time the thickness of the foam decreases. Therefore, in order to express the combined effect, thermal conductance per unit area, i.e., overall coefficient of heat transmission, is more appropriate than thermal conductivity. Thus, in the present work, the thermal conduction of the composite foam is evaluated in terms of overall coefficient of heat transmission.

Overall Coefficient of Heat Transmission Under Atmospheric Pressure

In general, when n materials of area A whose thermal conductivities are λ_1, $\lambda_2, \ldots, \lambda_n$ and whose thicknesses are $l_1, l_2, \ldots, l_n$ are layered perpendicular to heat flow, the thermal conductance $U_\perp$ is given by

$$\frac{1}{U_\perp} = \sum_{i=1}^{n} \frac{l_i}{A\lambda_i} \tag{1}$$

On the other hand, when the materials are layered parallel to heat flow, the thermal conductance $U_\parallel$, is given by

$$U_\parallel = \sum_{i=1}^{n} \frac{\lambda_i A_i}{l} \tag{2}$$

where A_i is the cross-sectional area of each component perpendicular to heat flow and l is its thickness.

The overall coefficient of heat transmission of the composite foam is to be determined by eqs. (1) and (2). In order to do so, a model having a spherical rigid foam in the middle, as shown in Figure 2(a), is conceived as a repetition unit. When the thickness of the composite foam under atmospheric pressure is h, the radius of the spherical rigid foam r, and the center-to-center distance of the

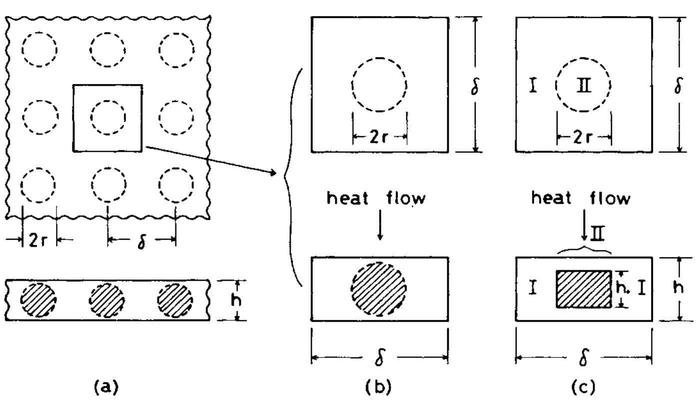

Fig. 2. Model of composite foam filled with spherical rigid foam.

sphere δ, the unit model becomes what is shown in Figure 2(b) having the top surface of a square with side δ and thickness h. A rigid foam sphere of radius r is in the middle. When heat flow occurs in this model in the direction indicated by an arrow in the figure, the heat flow expected inside is not exactly of one dimension. However, we assumed a steady one-dimensional heat flow for analysis here as Oka et al.[2] and several other authors[3–7] did in their analysis of thermal conductivity of two-phase materials. The model of Figure 2(b) is now replaced by the model shown in 2(c) for the sake of simplification. The new model has a cylinder of the same radius and volume as those of the rigid foam sphere of Figure 2(b). The height of the cylinder, h_0, is thus $4r/3$ from the equal-volume relation.

In order to obtain the thermal conductance of the unit model in the direction indicated by the arrow, section I on Figure 2(c), of only the matrix foam and section II on Figure 2(c), of the matrix foam and the rigid foam layered vertically, are considered separately. In consideration of the area, the thermal conductance of section I, U_{I}, is given by

$$U_{\mathrm{I}} = \lambda_1(\delta^2 - \pi r^2)/h \tag{3}$$

where λ_1 is the thermal conductivity of the matrix foam. From eq. (1) the thermal conductance of section II, U_{II}, is given by

$$\frac{1}{U_{\mathrm{II}}} = \frac{1}{\pi r^2}\left\{\frac{h - \frac{4}{3}r}{\lambda_1} + \frac{\frac{4}{3}r}{\lambda_2}\right\} \tag{4}$$

where λ_2 is the thermal conductivity of the spherical rigid foam.

Therefore, from the relation of eq. (2), the total thermal conductance of the unit model under atmospheric pressure, $[U_c]_{p=0}$, becomes

$$[U_c]_{p=0} = U_{\mathrm{I}} + U_{\mathrm{II}} = \frac{\lambda_1(\delta^2 - \pi r^2)}{h} + \frac{\pi r^2}{(h - \frac{4}{3}r)/\lambda_1 + \frac{4}{3}r/\lambda_2} \tag{5}$$

Thus, the thermal conductance per unit area, i.e., overall coefficient of heat transmission, $[u_c]_{p=0}$, is given by

$$[u_c]_{p=0} = \frac{[U_c]_{p=0}}{\delta^2} = \frac{1}{\delta^2}\left\{\frac{\lambda_1(\delta^2 - \pi r^2)}{h} + \frac{\pi r^2}{(h - \frac{4}{3}r)/\lambda_1 + \frac{4}{3}r/\lambda_2}\right\} \tag{6}$$

When structure parameters, n and ϕ, are defined as $r = nh$ and $\delta = \phi r = \phi nh$ expressing the radius of the rigid foam sphere, r, and the filling interval, δ, in terms of the thickness of the composite foam, eq. (6) is reduced to a following generalized form:

$$[u_c]_{p=0} = \frac{\lambda_1}{\phi^2 h}\cdot\frac{\phi^2\lambda_2 - \frac{4}{3}n(\lambda_2 - \lambda_1)(\phi^2 - \pi)}{\lambda_2 - \frac{4}{3}n(\lambda_2 - \lambda_1)} \tag{7}$$

When λ_1/λ_2 is put as κ_0, it is further reduced to

$$[u_c]_{p=0} = \frac{\lambda_1}{h}\cdot\frac{3 - 4n(1 - \kappa_0)(1 - \pi/\phi^2)}{3 - 4n(1 - \kappa_0)} \tag{8}$$

Overall Coefficient of Heat Transmission Under Hydrostatic Pressure

In the preceding section, the overall coefficient of heat transmission of the composite foam under atmospheric pressure was discussed. The overall coefficient of heat transmission of the composite foam under hydrostatic pressure is analyzed now. When the composite foam is subjected to hydrostatic pressure, compression deformation occurs not only in the direction of the thickness, but in the direction of the surface. However, in consideration of the conditions used in heat conduction experiments described later, it is assumed that the compression deformation in the direction of the surface is restricted and only that in the direction of the thickness is allowed to occur. Furthermore, the compression deformation of the rigid foam of the composite foam under hydrostatic pressure is considered extremely small and thus neglected. Thus, only the compression deformation of the matrix foam is considered.

In consideration of the above conditions, the unit model of Figure 2(b) will deform under hydrostatic pressure to Figure 3(b), which is again treated in a simplified form, Figure 3(c). When the matrix foam deforms owing to hydrostatic pressure and the compression strain ϵ is generated in the direction of the thickness, the dimension of each section of the unit model become what is shown in Figure 3(c′). The thermal conductivity of the matrix foam changes when the foam is compressed, and it is denoted as $[\lambda_1]_p$. Thus, the same treatment for Figure 3(c′) as carried out previously will give the overall coefficient of heat transmission, $[u_c]_p$, of the composite foam under hydrostatic pressure:

$$[u_c]_p = \frac{[\lambda_1]_p}{h(1-\epsilon)} \cdot \frac{3 - 4n(1-\kappa_p)(1-\pi/\phi^2)}{3 - 4n(1-\kappa_p)} \tag{9}$$

where $\kappa_p = [\lambda_1]_p/\lambda_2$. According to eq. (9), when the compression strain ϵ of the matrix foam and the thermal conductivity $[\lambda_1]_p$ under a given hydrostatic pressure are known, the overall coefficient of heat transmission of the composite

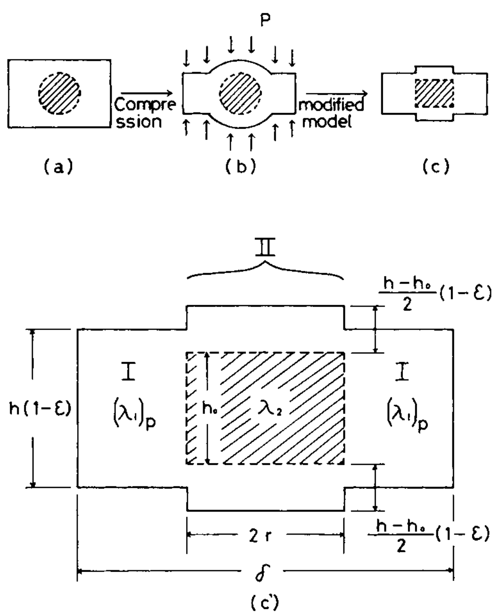

Fig. 3. Model of composite foam filled with spherical rigid foam under hydrostatic pressure.

foam can be estimated by putting structural parameters n and ϕ into the equation.

To obtain the thermal conductivity λ_1 of closed-cell foam, Oka et al.[2] used a unit model which contains a cubic cell gas in its center which they analyzed under the conditions of steady one-dimensional heat flow and thereby obtained the following equation:

$$\lambda_1 = \lambda_m \cdot \frac{1}{1 - v_a{}^{1/3} + v_a{}^{1/3}/\{1 - (1 - 1/\sigma)v_a{}^{2/3}\}} \tag{10}$$

where $\sigma = \lambda_m/\lambda_a$, and λ_m and λ_a are the thermal conductivities of the polymeric material and the gas phase, respectively; v_a is the volume fraction of the gas phase. When the compression strain, ϵ, of the flexible foam is generated in the direction of the thickness and the volume change of the polymer phase is neglected, the volume fraction of the gas phase becomes

$$v_a{}' = \frac{v_a - \epsilon}{1 - \epsilon} \tag{11}$$

By substituting eq. (11) for v_a in eq. (10), the thermal conductivity of the compressed foam, $[\lambda_1]_p$, becomes

$$[\lambda_1]_p = \lambda_m \cdot \left[1 - \left(\frac{v_a - \epsilon}{1 - \epsilon} \right)^{1/3} + \frac{\{(v_a - \epsilon)/(1 - \epsilon)\}^{1/3}}{1 - (1 - 1/\sigma)\{(v_a - \epsilon)/(1 - \epsilon)\}^{2/3}} \right]^{-1} \tag{12}$$

Therefore, by substituting eq. (12) into eq. (9), the overall coefficient of heat transmission of the composite foam compressed under hydrostatic pressure is estimated.

EXPERIMENTAL

Preparation of Composite Foam

The following will describe the preparation of a composite foam of the structure shown in Figure 1. Neoprene rubber foam (made by Showa Rubber) made for diving suits was used as a matrix foam, and as filling rigid foam epoxy foam prepared in our laboratory was used. The neoprene rubber with a skin on one surface is a closed cell foam. Its density is 0.394 g/cm^3 and its thickness, 5 mm. The spherical epoxy foams were prepared by adding 5 parts of an amine-type hardening agent, triethylenetetramine (TTA), and 5 parts of a foaming agent, azobisisobutyronitrile (made by Hikari Kagaku), for each 100 parts of Epikote 828 (made by Mitsubishi Yushi) and letting the mixture foam in a spherical mold 7 mm in diameter. The density of the obtained spherical epoxy foam is 0.391 g/cm^3. In order to fill the spherical foams in, hemispherical holes 7 mm in diameter are made in a square arrangement at intervals of δ on the side of the matrix foam with no skin. After the spherical epoxy foams are placed into these holes, another matrix foam with hemispherical holes made at the same intervals is bonded onto it to make a composite foam illustrated in Figure 1.

The structure parameters, i.e., h, n, and ϕ of eq. (9), of the composite foams used in the study are shown in Table I. The dimensions of the samples subjected to heat conduction experiment and flexural rigidity measurement are also shown in Table I.

TABLE I
Structural Parameters and Sample Sizes of Unfilled Foam and Composite Foams Filled with Spherical Rigid Foams

	Sample I	II	III	IV	V
Structural parameter					
ϕ	∞	4.57	4.00	3.43	2.86
n	0	0.35	0.35	0.35	0.35
Sample size, mm					
Bending rigidity test	30 × 130 × 10	48 × 130 × 10	42 × 130 × 10	36 × 130 × 10	30 × 130 × 10
Heat conduction test	180 × 180 × 10	180 × 180 × 10	180 × 180 × 10	180 × 180 × 10	180 × 180 × 10

Apparatus for Heat Conduction Experiment

Pressurizing method with flat plates, used in general, cannot be employed to apply uniform pressure to samples of a heterogeneity such as that of the composite foams treated in this study, as compression stress becomes uneven. Thus, an apparatus capable of applying a hydrostatic pressure onto both sides of the sample and measuring the thermal conductivity or the overall coefficient of heat transmission by comparative measurement was constructed. The diagram of the apparatus is illustrated in Figure 4. In order to eliminate the convection effect from the system, heat is made to flow only from the upper section of the apparatus to the lower section. The main body of the apparatus is made of a cylindrical air-tight vessel (1) 145 mm in inner diameter, which can resist the measurement pressures. The vessel, in turn, consists of three sections, I, II, and III. Between I and II is inserted the sample (2). The sample is fixed by the fringe of the air-tight vessel (1), and thus its deformation in the direction of the surface under hydrostatic pressure is restricted. Sections II and III are partitioned with a 4-mm copper plate (3). Section I is the side of the higher temperature. The temperature of the heat medium is regulated to be constant, i.e., 40°C, by a heater (9) and a slidac (10). Section II is the standard heat conduction medium, glycerin, whose thermal conductivity is known, used in this study. The thickness of the medium is 50 mm. Section III is the lower-temperature side, and the copper plate (3) is maintained at constant temperature (5°C) by an electronic cooling circulator. In order to apply various hydrostatic pressure onto the sample (2), the pressure inside the vessel is regulated with a control valve (12) connected to a high-pressure tank (11).

The upper surface temperature, T_1, the lower surface temperature, T_2, of the sample (2), and the lower surface temperature, T_3, of the standard heat conduction medium are measured with copper–constantan thermocouples (4), (5), and (6), respectively, and recorded automatically by a pen recorder (8). In order to eliminate errors owing to transverse heat flow, the diameter of the cylindrical

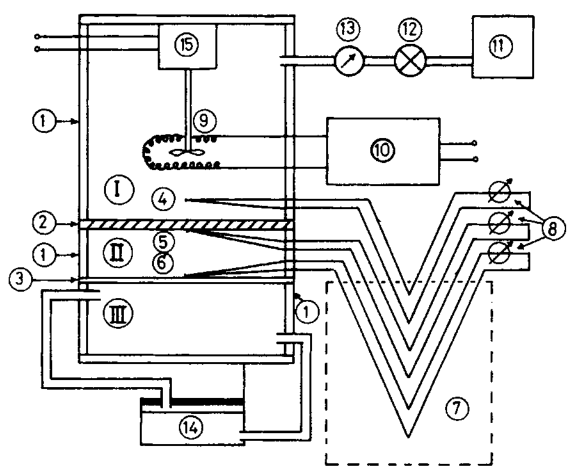

Fig. 4. Schematic diagram of apparatus for heat transmission experiment under hydrostatic pressure: (1) vessel; (2) sample; (3) copper plate; (4) copper–constantan thermocouple; (5) copper–constantan thermocouple; (6) copper–constantan thermocouple; (7) zero junction; (8) pen recorder; (9) heating filament; (10) slidac; (11) high-pressure tank; (12) pressure control valve; (13) pressure gauge; (14) electronic cooling circulator; (15) motor.

vessel is made sufficiently large in comparison with the thickness of the heat conduction layer, and the outer surface of the cylindrical vessel is covered with heat-insulating materials.

The procedure of the heat conduction experiment using this apparatus is the following. After the sample is set, the temperatures on both higher- and lower-temperature sides are regulated at T_1 = 40°C and T_2 = 5°C, respectively. Next, the pressure inside the apparatus is regulated to a given pressure with the control valve. If T_1, T_2, and the pressure are maintained at constant values for a sufficiently long time, T_2 will reach an equilibrium value in accordance with the overall coefficient of heat transmission of the sample. From T_1, T_2, and T_3, the overall coefficient of heat transmission of the sample, $[u_c]_p$, is then given by the following equation according to the principle of comparative measurement:

$$[u_c]_p = u_g \cdot \frac{T_2 - T_3}{T_1 - T_2} \tag{13}$$

where u_g is the overall coefficient of heat transmission of the standard glycerin layer, and since the thermal conductivity of glycerin, λ_g, is 0.2452 kcal/m-hr-°C and the thickness of the standard heat conduction layer, h_g, is 50 mm, u_g is λ_g/h_g = 4.904 kcal/m^2-hr-°C.

RESULTS AND DISCUSSION

Overall Coefficient of Heat Transmission and Coefficient of Heat Insulation

Experimental values of overall coefficient heat transmission of composite foams and unfilled foams under hydrostatic pressure are indicated as circles in Figure 5. The adequacy of eq. (9) is discussed by comparing these experimental values with those calculated according to the theoretical equation. Since eq. (9) contains the compression strain, ϵ, of the matrix foam under hydrostatic pressure, the compression stress–strain curve of the foam is necessary. Thus, a curve, shown in Figure 6, was obtained by subjecting the sample to the same conditions as for the heat conduction experiment, that is, the deformation in the direction of the surface was restricted. A value of the compression strain, ϵ, taken from this curve at a given pressure is put into eq. (12) to obtain the thermal conductivity $[\lambda_1]_p$, of the matrix foam under hydrostatic pressure. The thermal conductivities of neoprene rubber and gas, which are necessary for calculation by eq. (12), are λ_m = 0.108 kcal/m-hr-°C and λ_a = 0.0215 kcal/m-hr-°C at 20°C. The volume fraction of gas, v_a, of the matrix foam under atmospheric pressure is 0.63. When the value thus obtained for $[\lambda_1]_p$, the thermal conductivity of the spherical epoxy foam, λ_2 = 0.033 kcal/m-hr-°C, and various structural parameters shown in Table I are put into eq. (9), the overall coefficient of heat transmission of the composite foam under hydrostatic pressure is obtained.

The overall coefficient of heat transmission of the unfilled foam is also obtained from eq. (9) by substituting the structural parameters $\phi = \infty$ and $n = 0$. The calculated values of the overall coefficient of heat transmission, $[u_c]_p$, under pressures ranging from atmospheric to hydrostatic pressure corresponding to a 100-m depth in water are indicated as solid lines in Figure 5. As is apparent in the figure, the calculated values agree well with the experimental values over

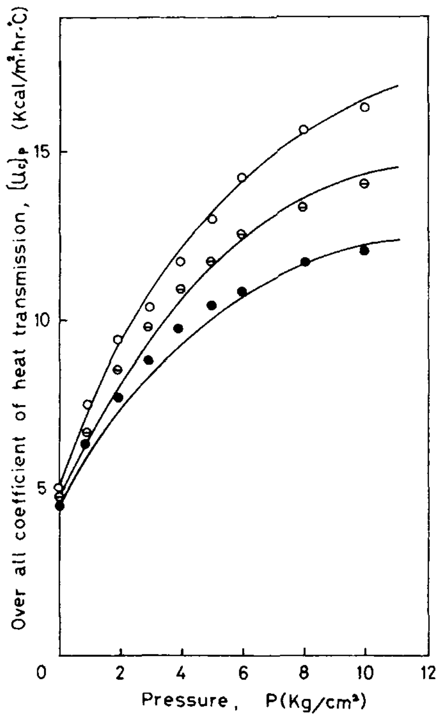

Fig. 5. Relation between overall coefficient of heat transmission and pressure: (O) $\phi = \infty$ (unfilled foam); (⊖) $\phi = 4.00$; (●) $\phi = 2.86$; —: calculated values with eq. (9).

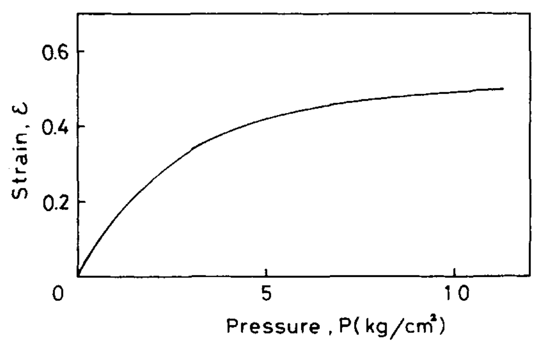

Fig. 6. Pressure–strain curve of unfilled foam.

the whole pressure range employed in the experiment. The same is found for the other composite foams whose results are not shown in the figure. Thus, the adequacy of eq. (9) was confirmed.

The overall coefficient of heat transmission of composite foams under hydrostatic pressure has been discussed so far. However, the coefficient of heat insulation, which is the reciprocal of the overall coefficient of heat transmission, is more appropriate for evaluating the heat-insulating property of foams than the overall coefficient of heat transmission itself. The coefficient of heat insulation, $[H_c]_p$, is thus given by

$$[H_c]_p = 1/[u_c]_p \tag{14}$$

In order to indicate clearly the filling effect of spherical rigid foams on the heat-insulating property or the coefficient of heat insulation, the increasing rate, ψ_H, in the coefficient of heat insulation owing to the composite structure is defined as follows:

$$\psi_H = \frac{[H_c]_{\phi,p} - [H_c]_{\phi=\infty,p}}{[H_c]_{\phi=\infty,p}} \tag{15}$$

where $[H_c]_{\phi=\infty,p}$ is the coefficient of heat insulation of unfilled foam ($\phi = \infty$) under pressure p, and $[H_c]_{\phi,p}$ is that of a composite foam with structural parameter ϕ under pressure p. The filling effect of spherical rigid foams, i.e., ψ_H, on the coefficient of heat insulation under various pressures, is thus obtained from eqs. (14) and (15). The relationship between the obtained values and the reciprocal of structural parameter ϕ, which indicates the filling density, is shown in Figure 7. According to the figure, the coefficient of heat insulation (heat insulation property) does not increase very much with increase in filling density $1/\phi$ under atmospheric pressure. However, under pressures corresponding to over 20 m depth in water, the coefficient of heat insulation increases remarkably along with $1/\phi$. Under pressure corresponding to 100 m of depth in water, ψ_H becomes 35% for the most closely filled composite foam ($1/\phi = 0.35$) used in the experiment, and the theoretical most closely filled composite foam ($1/\phi = 0.5$) will have ψ_H as large as 110%, that is, it possesses a heat-insulating property approximately twice as good as that of the unfilled foam.

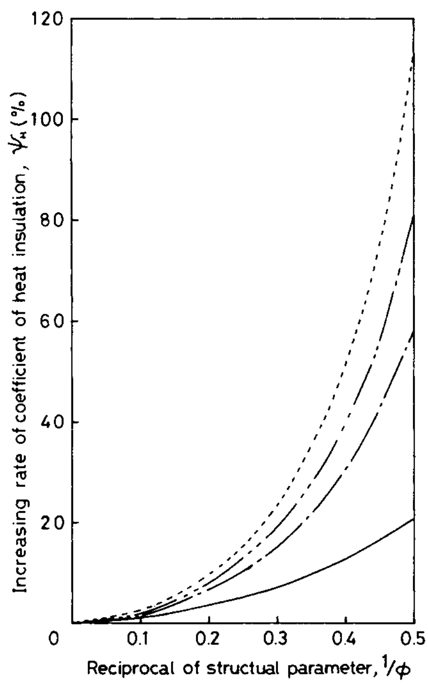

Fig. 7. Relation between increasing rate of coefficient of heat insulation and reciprocal of structural parameter: (—) $p = 0$ kg/cm^2; (-·-) $p = 2$ kg/cm^2; (—··—) $p =$ kg/cm^2; (- - - - - - -) $p = 10$ kg/cm^2.

Flexural Rigidity

The decrease in flexibility owing to filling of spherical rigid foams was examined by studying flexural rigidity. The flexural rigidity was measured by the three-point bending test under atmospheric pressure using composite foams of dimensions shown in Table I. The relationship between the flexural rigidity per unit width of the composite foam and the reciprocal of structural-parameter, ϕ, is shown as a solid line in Figure 8. As is clear from the figure, the increase in flexural rigidity owing to filling of spherical rigid foams is small; only an approximately 26% increase is observed for the most closely filled composite foam used in the experiment ($1/\phi = 0.35$) as compared with the unfilled foam. When only the thickness of unfilled foam is increased to obtain the same coefficient of heat insulation as that of a composite foam of a given ϕ value under pressure corresponding to a 100-m depth in water, the calculated flexural rigidity of the unfilled foam will be what is shown as a dotted line in Figure 8. As seen in the figure, the flexural rigidity of the most closely filled composite foam ($1/\phi = 0.35$) used in the experiment for example is as small as one half of that of an unfilled foam of the same heat-insulating property. Judging from the above-mentioned experimental results, it was confirmed that the use of composite foams filled with spherical rigid foams can accomplish to a considerable extent the aim of the present study, that is, to obtain foams of smaller flexural rigidity and higher heat-insulating property under high hydrostatic pressure.

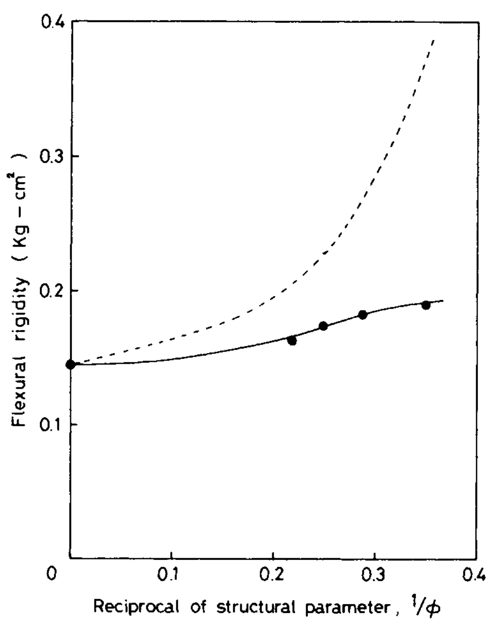

Fig. 8. Relation between flexural rigidity and reciprocal of structural parameter: (—●—) composite foam; (- - - - - -) unfilled foam.

CONCLUSIONS

In order to obtain foams possessing flexibility and at the same time heat insulation under high hydrostatic pressure, composite foams with spherical rigid foams filled in flexible rubber foam at certain intervals were prepared and their thermal conductivity and flexural rigidity were studied. The following points were found:

1. With a unit model having a spherical rigid foam in the middle, the thermal conduction of a composite foam was analyzed under the conditions of steady one-dimensional heat flow. Theoretical equations giving an overall coefficient of heat transmission under atmospheric and hydrostatic pressures were thus obtained. The adequacy of the theoretical equations was confirmed subsequently by the measurement of the overall coefficient of heat transmission of composite foams in an apparatus so constructed as to allow heat conduction experiments under hydrostatic pressures ranging from atmospheric to hydrostatic pressure corresponding to a 100-m depth in water.
2. The filling effect of spherical rigid foams on heat-insulating property was notable under hydrostatic pressures corresponding to a 20-m depth or more in water. Under a hydrostatic pressure corresponding to a 100-m depth in water, the coefficient of heat insulation of the most closely filled composite foam used in the experiment ($1/\phi = 0.35$) was larger than that of the unfilled foam by approximately 35%, while the theoretical most closely filled composite foam ($1/\phi = 0.5$) gives an approximately 110% increase.
3. Under hydrostatic pressure corresponding to a 100-m depth in water, the flexural rigidity of the most closely filled composite foam ($1/\phi = 0.35$) used in the experiment was approximately one half that of an unfilled foam of the same heat-insulating property.

The above findings indicate that composite foams can accomplish to a considerable extent the aim of the present study, that is, to obtain flexible and heat-insulating foams under high hydrostatic pressures.

References

1. S. Ohno and H. Kita, *Jpn. J. Ergonomics,* **5,** 246 (1969).
2. S. Oka and K. Yamane, *Jpn. J. Appl. Phys.,* **6,** 469 (1967).
3. D. J. Doherty, R. Hurd, and G. R. Lester, *Chem. Ind.,* 1340 (1962).
4. R. P. Sheldon and S. K. Lane, *Polymer,* **6,** 205 (1965).
5. A. L. Loeb, *J. Am. Ceram. Soc.,* **37,** 96 (1954).
6. H. W. Russel, Symposium on Heat Transfer Through Refractories and Insulation in Industrial Furnaces at the Annual Meeting, American Ceramics Society, 1934.
7. T. Watanabe, *J. Soc. Domestic Sanitary Eng. Jpn.,* **30,** 77 (1956).

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