DEWATERING OF GELS BY CONSTANT PRESSURE EXPRESSION

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The dewatering process of constant pressure expression was experimentally investigated with three kinds of bulk gels. While the structure of a gel is different from that of a solid liquid mixture, hydraulic pressure distribution in the gel approximately coincides with that calculated from the conventional theory of filtration during the first term of the process. This first term is able to be reasonably analysed as the filtration period. The subsequent process can be analysed as the consolidation period. Some of the liquid in the gel is mechanically inseparable, so as a rule it is essential to account for this liquid in analysis of the expression process for gelatinous materials. Results of electrical conductivity measurement of the gel indicate that the net free water almost corresponds with the water mechanically separable. The experimental results of agar-agar gel coincide favourably with the calculated results based on the conventional theory of expression and the compression permeability test data.

Introduction

Dewatering of gels by expression is widely used in various industrial fields not only for food manufacturing processes for agar-agar gel and dairy products, but also for pressing-induced dewatering of activated sludge and chemically gelled hazardous liquid spills. Most works have reported the rheological characteristics of gels^{5, 15, 16}. Few works, however, on the dewatering process of gels by expression²) have been reported. It is essential to investigate the dewatering process of gels in order to assess more rationally the process design and the selection of press to be installed.

In this study, the constant expression process of bulk gels was experimentally investigated. The variations of both moisture content and internal structure in the gel matrix were evaluated by measuring the electrical conductivity and the hydraulic pressure distribution in the gel matrix during the expression run. Furthermore, the expression process of gels under constant-pressure was analysed based on the conventional theory of expression^{6, 8, 11}). With the aid of compression permeability data, the theoretically predicted expression processes for gels were compared with the experimental results for agar-agar gel.

1. Experimental

1.1 Materials and preparation

Gels used in the present study were an agar-agar gel, a heavy oil(A) gel and a salad oil gel⁴). Agar-agar gel was prepared by the method of Watase¹⁵). A mixture of agar-agar powder and the deionized water was stirred for 1 hour and allowed to stand overnight at room temperature⁴). After preheating for 1 hour at 60°C, the mixture was boiled for 1 hour to dissolve the powder. The sol was transferred into

an expression cell of 70 mm internal diameter, and allowed to stand for about 15 hours at room temperature. The ratio of free liquid to gel, e , and the specific flow resistance, α , for agar-agar gel were measured by using a compression permeability cell (C-P cell)^{6, 7, 9}). The results are given in **Table 1** as a function of p_s .

Heavy oil(A) gel and salad oil gel were prepared by the following procedure. The gelling agent powder, amino acid- gelling agent for heavy oil(A) and stearic acid- for salad oil, was added with stirring^{4, 13}). After the mixture was heated for 1 hour at constant temperature, 140 °C for heavy oil and 90 °C for salad oil, the gel was made up in a similar manner to agar-agar gel.

1.2 Experimental apparatus and procedure

The experimental apparatus for constant pressure expression is schematically illustrated in **Fig.1(A)**. The cell consists of a piston and a cylinder of made both of brass and/or acrylic resin, as shown in **Fig.1(B)**. After mechanical pressure is applied to the piston, the decrease in gel thickness is measured by a dial gauge. In order to determine the electrical conductivity of gels, a pair of platinum electrodes (5 mm diameter) is mounted in the cell. The electrical resistance of gels is measured by an alternating current resistor (LCR meter). The cell constant is previously determined as the function of the distance between two electrodes with a 0.01 N KCl electrolyte.

The hydraulic pressure measuring apparatus is schematically shown in **Fig.2**. A subminiature pressure sensor (KYOWA,PS-5KB) is employed to measure directly the hydraulic pressure in the gel matrix.

2. Results and Discussion

2.1 Expression process of gels

In **Fig. 3 (A)**, the experimental results of gel thickness L and electrical conductivity of the gel κ vs. time $\sqrt{t}$

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Table 1 Compression permeability data for agar-agar gel.

void ratio e [-]	specific resistance α [m/kg]
$e=24.0$ ($p_s \leq 29.4$ Pa)	$\alpha=1.56 \times 10^{14}$ ($p_s \leq 29.4$ Pa)
$e=18.8-1.28 \ln p_s$ ($p_s > 29.4$ Pa)	$\alpha=2.19 \times 10^{13} p_s^{0.58}$ ($p_s > 29.4$ Pa)

Fig. 1 Experimental apparatus
(A) Schematic diagram of gel expression
(B) Compression permeability cell

Fig. 2 Schematic diagram of hydraulic pressure measuring apparatus

are plotted for agar-agar gel under a constant pressure of 155 kPa. The gel thickness L decreases linearly with time $\sqrt{\theta}$ and attains an equilibrium state at a time near $\sqrt{\theta} = 245 \text{ s}^{0.5}$. On the other hand, the electrical conductivity κ increases rapidly at time near $\sqrt{\theta} = 175 \text{ s}^{0.5}$ and maintains a constant value after $\sqrt{\theta} = 240 \text{ s}^{0.5}$.

Figure 3 (B) shows the experimental results for agar-agar gel, in which L vs. θ is converted to a relation between $-\Delta L / \Delta \sqrt{\theta + \theta_m}$ and $(\theta + \theta_m)$ according to the conventional method for expression analysis^{6, 8)}. The transition time θ_1 ($= 30000 \text{ s}$) in Fig. 3(B) coincides with time θ' ($= 30600 \text{ s}$) at which κ begin to increase rapidly in Fig. 3(A). It is considered that at this time the deliquoring mode switches to consolidation from filtration, as will be mentioned later. The same plots for experimental results of heavy oil(A) gel and salad oil gel are also illustrated in Fig. 4. At time $\theta < \theta_1$, the compact gel network structure begins to build up on the filter medium with squeezing out of the liquid. A compact gel refers to concentrated gel in this study in which the hydraulic pressure falls from p to close to zero while it remains constant p in the initial bulk gel. After the initial bulk gel disappears at $\theta = \theta_1$, a shrinking process described

Fig. 3 Results of constant pressure expression for agar-agar gel, (A) relation between L , κ , and $\sqrt{\theta}$, (B) relation between $-\Delta L / \Delta \sqrt{\theta + \theta_m}$ and $(\theta + \theta_m)$

Fig. 4 Relation between $-\Delta L / \Delta \sqrt{\theta + \theta_m}$ and $(\theta + \theta_m)$ for oil gel

as consolidation of the concentrated gel continues to an equilibrium state with applied pressure p .

2.2 Properties of water in gels

In general, gels are constructed of a macromolecular network in which is enclosed a large quantity of water. It is widely noted that the water in macromolecular gels is present in two states, *i.e.*, free water and bound water. Furthermore, electrochemical, dilatometric and nuclear magnetic resonance measurements have made it clear that free water can be further classified into two states, *i.e.*, half-bounded water and net free water^{3, 12)}. In this study, the relationship between the electrical conductivity κ and the water content for agar-agar gel was determined experimentally by using a platinum black electrode in a

Fig. 5 Relation between electrical conductivity and water content

Fig. 6 Relation between ratio of concentrated gel to dry gel mass and reciprocal pressure at the equilibrium state

conductometric cell ($1.0 \times 1.0 \text{ cm}^2$ area). The platinum electrode was in the C-P cell (5 mm diameter) and the silver paste electrodes³⁾ were positioned on either side of the gel (6 mm diameter). A plot of $\log \kappa$ vs. water content ($100 - s_g$) is shown in Fig. 5, where s_g is the mass fraction of dry solid in the initial bulk gel customarily represented as a percentage. Suzuki *et al.*¹²⁾ observed a similar relationship between κ and the water content for agar-agar gel. Water contents of less than 20% and 56% correspond to the bound water and the half-bound water including bounded water, respectively.

In Fig. 6, the experimental values of the ratio (w_∞/w_d) are plotted with respect to the reciprocal of the pressure ($1/p$), where w_∞ is the gel mass containing free liquid at the

Fig. 7 Comparison of experimental and predicted results for hydraulic pressure p_L in concentrated gel

Fig. 8 Comparison of experimental and predicted results for hydraulic pressure distributions in concentrated gel

equilibrium state of expression and w_d is the dry mass of the gel. These relationships are similar to the water adsorption isotherm¹⁾ in the case of food colloids which can be approximated as a sigmoid in shape. The limiting value of (w_∞/w_d) for ($1/p$) $\rightarrow 0$, i.e., infinite compressive pressure $p \rightarrow \infty$, approaches 2.3 for agar-agar gel. If this limiting value is replaced by the parameter β , the mass of the gel is equal to $\beta \cdot w_d$. The gel is represented as an extreme gel in this study. This value of β shows favourable coincidence with the value obtained from the water content of 56% in Fig. 5. The values of β for heavy oil(A) gel and salad oil gel were approximately 1.8 and 1.2, respectively. It is considered that the value of ($\beta - 1$) w_d corresponds to water unable to be removed by mechanical methods.

2.3 Measurements of hydraulic pressure in gel matrix

The variation of hydraulic pressure p_L in the gel matrix is illustrated in Fig. 7 with the deliquored volume v , where the value of x indicates distance from the filter medium. As expression proceeds and the surface of the concentrated gel reaches the sensor, hydraulic pressure begins to fall and continues to dwindle. Based upon these experimental data, hydraulic pressure distributions are plotted in Fig. 8, which shows the normalized hydraulic pressure¹⁰⁾ (p_L/p) vs. the normalized distance (x/L_c). L_c is the thickness of the concentrated gel matrix. While in the filtration period the (p_L/p) distributions are a function of

(x/L_c) alone and independent of the proceeding of expression. The hydraulic pressure at any normalized point decreases with the proceeding of expression in the consolidation period. The degree of expression is shown in Fig.8 with average consolidation ratio U_c defined later by Eq.(8). Although the p_L -distribution for a moderately compressible filter cake is approximated as a sine curve⁷⁾ (broken line), the experimental results for agar-agar gel indicate higher compressive characteristics.

2.4 Analysis of expression process for gels

As mentioned above, the expression process for gels can be reasonably analysed firstly by the filtration theory and secondly by the consolidation theory.

1) Filtration period In this period, the amount of concentrated gel matrix grows and the initial bulk gel starts to disappear. The filtration ratio U_f under constant pressure conditions is written as follows^{6, 8)}

$$U_f = \frac{L_0 - L}{L_0 - L_1} = \frac{i\sqrt{K_\omega}}{\omega_0} (\sqrt{\theta_f + \theta_m} - \sqrt{\theta_m}) \quad (1)$$

$$K_\omega \equiv 2pps / \mu \alpha_{av} \rho_{ex}^2 (1 - ms) \quad (2)$$

where L_0 is the thickness of initial bulk gel, L_1 the thickness of concentrated gel at the end of filtration period ($\theta = \theta_1$), i the number of drainage surfaces, ω_0 the volume of extreme gel per unit sectional area, θ_m the assumed filtration time corresponding to medium resistance, and K_ω the modified filtration coefficient. s is the mass fraction of extreme gel in the gel, i.e., $\beta s_g/100$.

The value ω_0 for expression of gels is given with the assumption of additive property by

$$\omega_0 = \beta \cdot \left(\frac{w_d}{\rho_{ex}} \right) = \frac{\{\rho + \rho_p(\beta - 1)\} \cdot w_d}{\rho \rho_p} \quad (3)$$

where ρ_{ex} is the density of extreme gel and ρ_p the true density of the gel powder. In the case of agar-agar gel, the value of ρ_{ex} is given as 1105 kg/m³ with $\beta = 2.3$ and $\rho_p = 1280$ kg/m³.

The mass ratio of concentrated gel to extreme gel m can be written as

$$m = 1 + \frac{\rho \cdot e_{av}}{\rho_{ex}} = 1 + \frac{\rho(L_1 - \omega_0)}{\rho_{ex}\omega_0} \quad (4)$$

where e_{av} is the average volume ratio of free liquid to extreme gel.

The only liquid which can be removed by mechanical compression of gels is the free liquid annexed to extreme gel. Therefore, it is essential to take into account the bound and half-bound water rather than the dry mass of materials. This is rather common in the case of processes in which biological or microbial materials are concerned. Examples are culture solution or activated sludge. Because they sometimes have much inner cellular and/or bound liquid, the mass obtained from thermal drying has to be revised to a proper value for the mechanical separation process.

The basic flow equation for constant-pressure filtra-

tion can be written as^{9, 10)}

$$u_\omega = \frac{1}{\mu \rho_{ex} \alpha} \cdot \frac{\partial p_L}{\partial \omega} \quad (5)$$

where α is the local specific resistance and u_ω is the apparent relative velocity of the liquid^{8, 10)}. The constant-pressure filtration period in the gel expression process can be calculated theoretically based on Eqs.(1) – (5) and the compression permeability data. The calculated results are shown in Figs. 3, 7 and 8 by solid lines. Good agreement is observed between experimental and predicted values. It is confirmed that the process is able to be reasonably analysed over the period in which the filtration theory is applicable.

2) Consolidation period In this period, consolidation of the concentrated gel proceeds. The basic differential equations for the consolidation period are written as^{6, 8)}

$$\frac{\partial p_s}{\partial \theta_c} = C_e \frac{\partial^2 p_s}{\partial \omega^2} \quad (6)$$

$$C_e \equiv \frac{1}{\mu \alpha_{av} \rho_{ex} (-de/dp_s)} \quad (7)$$

where θ_c is the consolidation time, and C_e is the modified consolidation coefficient. The average consolidation ratio U_c under constant-pressure expression is given by¹¹⁾

$$U_c = \frac{L_1 - L}{L_1 - L_\infty} = 1 - \sum_{n=1}^{\infty} \frac{1}{(2n-1)} \left[\frac{2p}{(2n-1)\pi} - \frac{i}{\omega_0} \int_0^{\omega_0/i} B_1 \cdot \sin \left\{ \frac{(2n-1)\pi i \xi}{2\omega_0} \right\} d\xi \right] \times \left[1 - \exp \left\{ -\frac{(2n-1)^2 \pi^2 t^2 C_e \theta_c}{4\omega_0^2} \right\} \right] / \sum_{n=1}^{\infty} \frac{1}{(2n-1)} \times \left[\frac{2p}{(2n-1)\pi} - \frac{i}{\omega_0} \int_0^{\omega_0/i} B_1 \cdot \sin \left\{ \frac{(2n-1)\pi i \xi}{2\omega_0} \right\} d\xi \right] \quad (8)$$

where L_∞ is the thickness of the gel matrix when $\theta_c \rightarrow \infty$, and p_{s1} is the local value of p_s when $\theta_c = 0$.

The consolidation process for gels can be calculated theoretically based on Eqs.(6) – (8). In order to simplify the calculation, C_e is assumed to be constant. It is evaluated¹¹⁾ as the value corresponding to the arithmetic mean value of compressive pressure at the beginning and end of the consolidation period. In Fig. 9, the experimental results of bulk gel thickness L vs. time $\sqrt{\theta}$ for agar-agar gel are plotted under various expression pressures. The solid lines in Figs. 3 and 9 represent the calculated results based on the theory and the compression permeability data mentioned above. They show good agreement with the experimental results over the entire period for expression of gels. In Figs. 7 and 8, the experimental results for hydraulic pressure distribution in concentrated gel are also compared with the calculated results. It is also confirmed that this calculation method is applicable to the analysis of expression processes for gels.

For expression of gels used in this study, the influence of what is called secondary consolidation⁸⁾ was

Fig. 9 Comparison of experimental and predicted results for bulk gel thickness L

negligibly small. However, more extensive experimentation should be required to clarify whether this is unique to gels used in this study or not. For analysis of ductile gels like casein curd⁽⁴⁾ and gelatin gel⁽⁴⁾, it is necessary to take into account the creep behaviour.

Conclusions

The dewatering process of bulk gels under constant pressure expression was experimentally investigated by means of evaluating the change in liquid content. This was conducted by measuring the electrical conductivity and the hydraulic pressure distribution in the gel matrix. These results were summarized and the following conclusions were obtained.

(1) Although the structure of gel is different from that of solid-liquid mixtures, the dewatering process of gels by expression can be reasonably analysed as a filtration period followed by a consolidation period as is in the process of solid-liquid mixture.

(2) For accurately determining the characteristic values of expression, for example the specific flow resistance of the gel or the volume of removable liquid, it is essential to estimate the mass and volume of the extreme gel. The dry mass of the gel does not correspond to the flow resistance or the void volume of the gel matrix.

(3) The experimental results of agar-agar gel coincide favourably with the calculated results based on the conventional theory of expression and the compression permeability test data.

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Nomenclature

C_c	= modified consolidation coefficient	[m ² /s]
e	= local volume ratio of free liquid to extreme gel	[-]
i	= number of drainage surfaces	[-]
K_ω	= modified filtration coefficient	[m ² /s]
L	= thickness of gel matrix	[m]
L_0	= thickness of initial bulk gel	[m]
L_c	= thickness of concentrated gel matrix	[m]
m	= mass ratio of concentrated gel to extreme gel	[-]

p	= applied pressure	[Pa]
p_L	= local hydraulic pressure	[Pa]
p_s	= local compressive pressure	[Pa]
s	= mass fraction of extreme gel in bulk gel	[-]
s_g	= mass fraction of dry solid in the initial bulk gel	[%]
U_c	= average consolidation ratio	[-]
U_f	= filtration ratio	[-]
u_ω	= apparent liquid velocity relative to gel matrix	[m/s]
w_d	= dry mass of gel per unit medium area	[kg/m ²]
x	= distance from filter medium	[m]
α	= local specific resistance of concentrated gel	[m/kg]
β	= conversion factor from dry to extreme gel mass	[-]
θ	= time	[s]
θ_c	= consolidation time	[s]
θ_m	= fictitious filtration time corresponding to medium resistance	[s]
κ	= electric conductivity	[S/m]
μ	= viscosity of liquid	[Pa·s]
ξ	= relative position in gel matrix	[-]
ρ	= density of liquid	[kg/m ³]
ρ_{ex}	= density of extreme gel	[kg/m ³]
ρ_p	= true density of gel powder	[kg/m ³]
ω	= extreme gel volume per unit area lying between the medium and an arbitrary position in gel	[m]
ω_0	= total extreme gel volume per unit area	[m]
<Subscript>		
av	= average value	
l	= value at the end of filtration period ($\theta = \theta_l$)	
∞	= value at the consolidation equilibrium ($\theta_c = \infty$)	

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