

# COMBINED OPERATION OF ELECTROSMOTIC DEWATERING AND MECHANICAL EXPRESSION

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The use of electroosmotic dewatering has just begun in industrial practice. In some forms of apparatus an electric field and mechanical pressure are applied simultaneously to a sludge. Considering the tortuosity of a flow path and the effect of the hydraulic pressure profile in a material, we have successfully developed a theory of the dewatering where only an electric field is applied to the material.<sup>1)</sup> In this study, we extend the previous theory to the operation in which electroosmotic dewatering and mechanical expression occur concurrently.

## 1. Experimental

The experimental apparatus is the same as the previous one,<sup>1)</sup> which has essentially the form of a compression cell. A bentonite-deionized water slurry was pre-consolidated in the apparatus under a pressure  $p_{s1}$  of 98.1 kPa, resulting in a semisolid material with a uniform void ratio  $e_1$ . Then, D.C. voltage  $V_T$  and a mechanical pressure  $p$  were applied to the material. The electric current density  $i$  was held constant. The liquid could flow out only through the bottom

drainage surface of the cell. The volume of removed liquid was measured with the lapse of time  $\theta$ .

## 2. Theory

When both an electric field and a liquid pressure difference exist in a porous material, the apparent liquid velocity  $q$  through the material is represented by<sup>1,2)</sup>

$$q = \frac{1}{\mu\alpha\rho_s} \left( \frac{\sigma_s i \rho_E}{\varepsilon} - \frac{\partial p_s}{\partial \omega} \right) \quad (1)$$

where  $\mu$  denotes the viscosity of liquid;  $\alpha$ , the specific hydrodynamic resistance;  $\rho_s$ , the true density of solids;  $\sigma_s$ , the effective charge on solid surface per unit volume of solids;  $\rho_E$ , the specific electric resistance;  $\varepsilon$ , the porosity;  $p_s$ , the solid compressive pressure; and  $\omega$ , the moving material coordinate.

The basic differential equation which controls the progress of electroosmotic dewatering is given by<sup>1)</sup>

$$\frac{\partial e}{\partial \theta} = \frac{\partial q}{\partial \omega} = \frac{\partial}{\partial \omega} \left\{ \frac{1}{\mu\alpha\rho_s} \left( \frac{\sigma_s i \rho_E}{\varepsilon} - \frac{\partial p_s}{\partial \omega} \right) \right\} \quad (2)$$

where  $e$  denotes the local void ratio. Eq. (2) is reduced

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to the consolidation equation<sup>3)</sup> if  $i=0$ . When an electric field and a mechanical pressure are applied simultaneously to the material, the initial and boundary conditions for Eq. (2) can be described as

$$p_s = p_{s1} \quad \text{at } \theta = 0 \quad (3)$$

$$p_s = p \quad \text{at } \omega = 0 \text{ (drainage surface)} \quad (4)$$

$$\frac{\partial p_s}{\partial \omega} = \frac{\sigma_s i \rho_E}{\varepsilon} \quad \text{at } \omega = \omega_0 \text{ (upper electrode)} \quad (5)$$

$$e \geq e_\infty \quad (6)$$

Equation (4) is obtained from the force balance, provided that the liquid pressure is zero at the drainage surface. Impermeable condition at the upper electrode leads to Eq. (5).<sup>1)</sup>  $e_\infty$  in Eq. (6) represents the critical void ratio at which electroosmotic flow does not occur.<sup>1)</sup>

To solve Eq. (2), the right-hand side is represented by finite difference forms in place of derivatives. Numerical calculations based upon the Runge-Kutta-Gill method are then made to obtain the change of  $e$  with time  $\theta$  and a position  $\omega$ . The liquid removed per unit drainage area  $v$  is calculated by

$$v = \int_0^{\omega_0} (e_1 - e) d\omega \quad (7)$$

### 3. Results and Discussion

**Figure 1** compares the combined operation of electroosmotic and mechanical dewatering with those individual operations. In the electroosmotic dewatering, the decrease of moisture starts from the upper electrode, as shown in **Fig. 2**. On the other hand, the mechanical consolidation proceeds from the lower electrode, if the upper one acts as an impermeable wall. The dewatering in the combined operation proceeds from both upper and lower electrodes, thus leading to a higher dewatering rate than in the individual operations, as shown in **Fig. 1**. The lines in the figure represent the theoretical results calculated by Eq. (2). For the electroosmotic dewatering, Eq. (2) was solved with the boundary condition that  $p_s = p_{s1}$  at  $\omega = 0$ , while in the mechanical consolidation  $i$  in Eqs. (2) and (5) was set to be zero. In the calculation, physical properties of bentonite cake were obtained from the previous correlations.<sup>1)</sup> It can be seen from the figure that reasonable fits between theory and experiments are attained.

**Figure 3** shows changes in the internal conditions of the material under the combined operation. In the figure,  $\omega/\omega_0$  represents an arbitrary position in the material ( $\omega/\omega_0 = 0$  at the lower electrode, and  $\omega/\omega_0 = 1$  at the upper electrode). It can be seen from the figure that the dewatering proceeds from both upper and lower electrodes. The broken lines in the figure

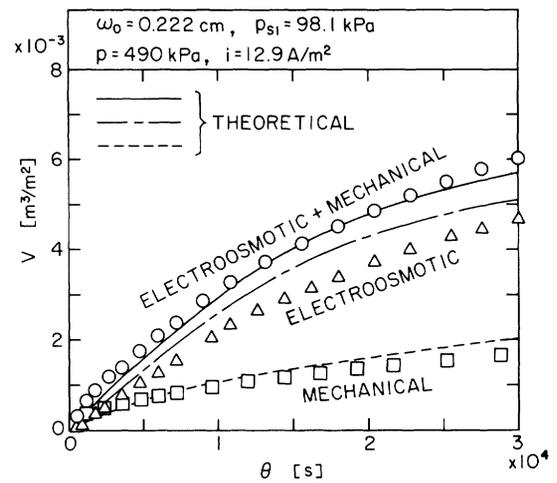


Fig. 1. Comparison of theory and experiment

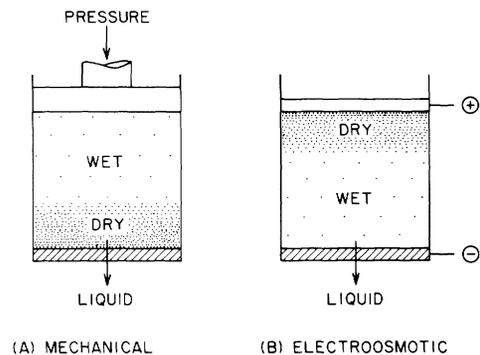


Fig. 2. Schematic diagram showing the progress of dewatering

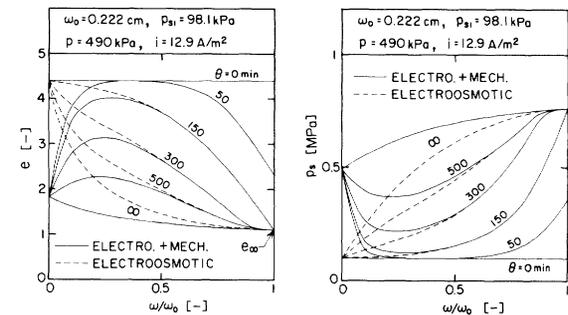


Fig. 3. Change of internal condition of the material with time

represent the  $e$ - and  $p_s$ -distributions of the electroosmotic dewatering. The difference between the solid and broken lines accordingly represents the contribution of the mechanical consolidation.

**Figure 4** compares the electric energy consumption  $J$  under the combined operation with that of the electroosmotic dewatering; both were calculated by

$$J = \int_0^\theta i V_T d\theta \quad (8)$$

where  $V_T$  denotes the voltage applied to the electrodes.

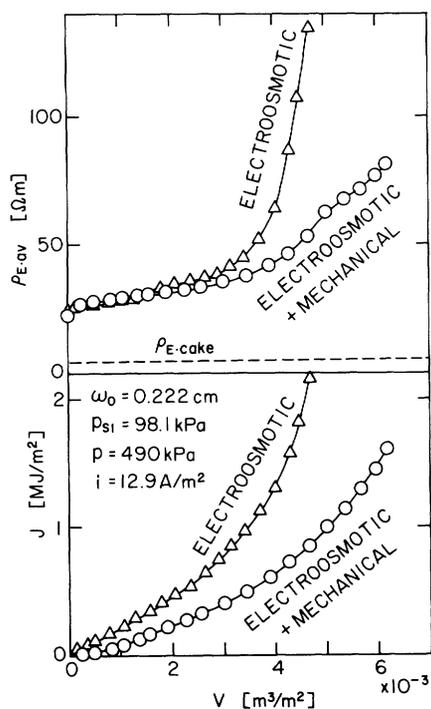


Fig. 4. Energy consumption under electroosmotic dewatering and under electroosmotic-mechanical combined dewatering

$\rho_{E.av}$  in the upper half of the figure is the average specific electric resistance calculated by

$$\rho_{E.av} = V_T / i / (\text{cake thickness}) \quad (9)$$

It consists of the cake resistance and the contact resistance between the electrode and the material. Since the theoretical average cake resistance  $\rho_{E.cake}$  of bentonite is a unique function of  $v$  and does not depend on the mode of dewatering, as shown in the figure (broken line), the difference between  $\rho_{E.av}$  in the two operations is based on the difference in contact resistances. The enormous improvement in energy consumption under the combined operation is consequently due to both the contribution of the mechanical dewatering and the decrease of contact

resistance. Incidentally, the energy for mechanical expression is so small to be a few-thousandths of that for electroosmosis if it is calculated by (expression pressure  $\times$  decrease of cake thickness).

#### Nomenclature

$e$	= local void ratio	[—]
$e_1$	= void ratio of pre-consolidated material	[—]
$e_{\infty}$	= critical void ratio; if $e < e_{\infty}$ electroosmosis does not occur	[—]
$i$	= electric current density	[A/m <sup>2</sup> ]
$p$	= expression pressure	[Pa]
$p_s$	= local solid compressive pressure	[Pa]
$p_{s1}$	= pre-consolidation pressure	[Pa]
$q$	= apparent velocity of liquid	[m/s]
$V_T$	= applied voltage	[V]
$\alpha$	= specific hydrodynamic resistance	[m/kg]
$\varepsilon$	= local porosity	[—]
$\theta$	= dewatering time	[s]
$\mu$	= liquid viscosity	[Pa·s]
$\rho_E$	= local specific electric resistance	[Ω·m <sup>2</sup> /m]
$\rho_{E.av}$	= average specific electric resistance calculated by $\rho_{E.av} = V_T / i / (\text{cake thickness})$	[Ω·m <sup>2</sup> /m]
$\rho_{E.cake}$	= average specific electric resistance of material	[Ω·m <sup>2</sup> /m]
$\rho_s$	= true density of solid	[kg/m <sup>3</sup> ]
$\sigma_s$	= effective charge on solid surface per unit volume of solids	[C/m <sup>3</sup> ]
$\omega$	= variable representing an arbitrary position in the material, i.e. volume of solids per unit cross-sectional area measured from the lower electrode	[m <sup>3</sup> /m <sup>2</sup> ]
$\omega_0$	= total volume of solid per unit cross-sectional area	[m <sup>3</sup> /m <sup>2</sup> ]

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