FUNDAMENTAL STUDY ON ELECTROOSMOTIC DEWATERING OF SLUDGE AT CONSTANT ELECTRIC CURRENT

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It is possible to apply electroosmosis to dewatering of sludge.

In this paper, the mechanism of electroosmotic dewatering of compressible sludge under condition of constant electric current was discussed, based on the model of electroosmotic flow through the particle packed bed, and the effects of the operating conditions on the rate of electroosmotic dewatering and the electric power consumption were theoretically analysed. The equations obtained theoretically were confirmed experimentally under condition of constant electric current with the compressible sludges such as white clay, magnesium hydroxide and bentonite. Theoretical equations were available for the design of electroosmotic dewatering apparatus. The electroosmotic dewatering was particularly effective for gelatinous sludges.

Introduction

Mechanical dewatering operations such as gravitational method, centrifugal method, compression, and vibrational method have so far been used and have been studied theoretically and experimentally. But mechanical dewatering is very difficult for the precipitates of colloidal particles and the gelatinous sludges.

A particle dispersed in liquid has electric potential, the so-called ζ-potential. When particles are dispersed in water, ζ-potential is about 0.01 to 0.1 volt. Electroosmosis generated in the sludge may be used in the dewatering of sludge[2,4,5].

In previous studies[1], electroosmosis was applied to the dewatering of sludge such as peat, soil, magnesium hydroxide, beating pulp, casein, and the like. However, the relation between operating conditions and the dewatering rate was not clear. Komagata[3] had proposed a theoretical dewatering equation under condition of constant electric voltage by using the capillary tubes model and studied the characteristics of electroosmotic dewatering and the efficiency of electroosmotic dewatering by use of clay, nickel hydroxide, and powder coal. But this theoretical analysis is not adequate for the compressible sludge because his theory is concerned with investigation of incom-

pressible sludge.

The present study was performed to obtain fundamental design equation of electroosmotic dewatering under conditions of constant electric current. Then the effects of the operating conditions (i. e. electric current density, sludge concentration, height of sludge bed, etc.) on the rate of electroosmotic dewatering and electric power consumption were theoretically analysed by use of a model of electroosmotic flow through the particle packed bed. The equations obtained theoretically were confirmed experimentally under condition of constant electric current with the compressible sludge such as white clay, magnesium hydroxide and bentonite. Bentonite sludge was used as an example of a gelatinous substance. Consequently, the theoretical equations are available for the design equations of electroosmotic dewatering apparatus.

Theoretical Analysis of Electroosmotic Dewatering for Compressible Sludge at Constant Electric Current

The electroosmotic dewatering model for compressible sludge under condition of constant electric current is shown in **Fig. 1**. A constant electric current density I_0 is passed through the sludge bed. The polarity of electrodes is selected according to the polarity of ζ-potential of particles in order to remove water in the sludge downwards. In the case of compressible sludge, the height of the sludge bed decreases with the dewatering of sludge and the initial height of sludge bed H_0 becomes H_t at time t. In Fig. 1, part I is the dewatering sludge bed

and part II is the dewatered sludge bed. The values of ε_{1w} and ε_{2w} are the porosity of water part in each bed and ε_{1a}, ε_{2a} the porosity of air part in each bed, and λ_1, λ_2 the equivalent specific conductivity of each bed, respectively. These values are assumed to be constant throughout each bed.

As shown in Fig. 1, the electroosmotic velocity in the dewatering sludge bed u_E is represented by the Debye-Hückel equation as follows:

$$u_E = \frac{\zeta D E_1}{\kappa \pi \mu}\left(\frac{1}{300}\right)^2 \tag{1}$$

where ζ, D, κ, μ, and E_1 are the ζ-potential of particles, the dielectric constant of liquid, the factor of particle shape, the viscosity of liquid, and the strength of electric field in the dewatering sludge bed, respectively. The strength of electric field in the dewatering sludge bed E_1 is expressed by Ohm's law as follows:

$$E_1 = \frac{I_0}{\lambda_1} \tag{2}$$

By substituting Eq. (2) into Eq. (1), u_E is rewritten as follows:

$$\left. \begin{aligned} u_E &= \alpha \frac{I_0}{\lambda_1} \\ \alpha &= \frac{\zeta D}{\kappa \pi \mu}\left(\frac{1}{300}\right)^2 \end{aligned} \right\} \tag{3}$$

where α is the electroosmotic coefficient which can be obtained experimentally. If the experimental conditions are defined, α, I_0, and λ_1 become constant. Therefore u_E becomes also constant.

The electroosmotic flow rate q_E is expressed by Eq. (4).

$$q_E = A \varepsilon_{1w} u_E \tag{4}$$

Substituting Eq. (3) into Eq. (4) and integrating Eq. (4), the dewatered volume by electroosmosis Q_E can be written as follows:

$$Q_E = \int_0^t q_E dt = A \varepsilon_{1w} u_E \int_0^t dt = A \varepsilon_{1w} \alpha \frac{I_0}{\lambda_1} t \tag{5}$$

Eq. (5) shows that Q_E is proportional to t and I_0. The relation between the electric power consumption W and the dewatering time t is obtained by the following method. The voltage V_t applied to the electrodes at the dewatering time t is shown as

$$\begin{aligned} V_t &= V_1 + V_2 = E_1 H_1 + E_2 H_2 \\ &= I_0\left(\frac{H_1}{\lambda_1} + \frac{H_2}{\lambda_2}\right) \end{aligned} \tag{6}$$

where V_1 and V_2 are the voltage applied to each bed I, II in this model. Taking the material balances of the liquid and the solid for the sludge bed in Fig. 1.

$$\left. \begin{aligned} & AH_1\varepsilon_{1w} + AH_2\varepsilon_{2w} + A\varepsilon_{1w}\int_0^t u_E dt = AH_0\varepsilon_{1w} \\ & \qquad\qquad\qquad\qquad\text{(for liquid)} \\ & A(H_0 - H_1)\{1 - (\varepsilon_{1w} + \varepsilon_{1a})\} = AH_2\{1 - (\varepsilon_{2w} + \varepsilon_{2a})\} \\ & \qquad\qquad\qquad\qquad\text{(for solid)} \end{aligned} \right\} \tag{7}$$
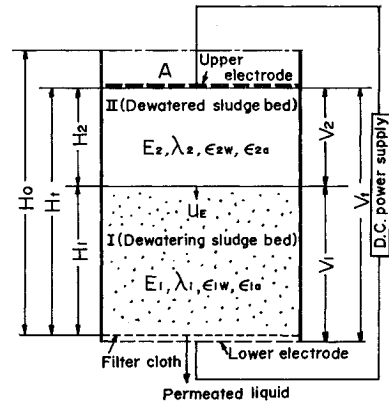
Fig. 1 Schematic diagram of electroosmotic dewatering at constant electric current

From above equations, H_1 and H_2 are obtained as follows:

$$\left. \begin{aligned} H_1 &= H_0 - \frac{\varepsilon_{1w}\{1 - (\varepsilon_{2w} + \varepsilon_{2a})\}}{\varepsilon_{1w}(1 - \varepsilon_{2a}) - \varepsilon_{2w}(1 - \varepsilon_{1a})}\int_0^t u_E dt \\ H_2 &= \frac{\varepsilon_{1w}\{1 - (\varepsilon_{1w} + \varepsilon_{1a})\}}{\varepsilon_{1w}(1 - \varepsilon_{2a}) - \varepsilon_{2w}(1 - \varepsilon_{1a})}\int_0^t u_E dt \end{aligned} \right\} \tag{8}$$

Substitution of Eq. (8) into Eq. (6) gives

$$V_t = \frac{I_0}{\lambda_1}\left[\frac{\alpha I_0 \varepsilon_{1w}}{\varepsilon_{1w}(1 - \varepsilon_{2a}) - \varepsilon_{2w}(1 - \varepsilon_{1a})}\left\{\frac{1 - (\varepsilon_{1w} + \varepsilon_{1a})}{\lambda_2} - \frac{1 - (\varepsilon_{2w} + \varepsilon_{2a})}{\lambda_1}\right\}t + H_0\right] \tag{9}$$

Hence, the electric power consumption W is written as Eq. (11) from the following equation (10).

$$W = \int_0^t AI_0 V_t dt = AI_0\int_0^t V_t dt \tag{10}$$

$$W = \frac{AI_0^2}{\lambda_1}\left[\frac{\varepsilon_{1w}}{\varepsilon_{1w}(1 - \varepsilon_{2a}) - \varepsilon_{2w}(1 - \varepsilon_{1a})}\left\{\frac{1 - (\varepsilon_{1w} + \varepsilon_{1a})}{\lambda_2} - \frac{1 - (\varepsilon_{2w} + \varepsilon_{2a})}{\lambda_1}\right\}\frac{\alpha I_0}{2}t^2 + H_0 t\right] \tag{11}$$

If the porosity of the air part in each sludge bed is much smaller than that of water part, ε_{1a} and ε_{2a} can be neglected. Therefore, Eq. (11) is approximately written as Eq. (12).

$$W = \frac{AI_0^2}{\lambda_1}\left\{\frac{\varepsilon_{1w}}{\varepsilon_{1w} - \varepsilon_{2w}}\left(\frac{1 - \varepsilon_{1w}}{\lambda_2} - \frac{1 - \varepsilon_{2w}}{\lambda_1}\right)\frac{\alpha I_0}{2}t^2 + H_0 t\right\} \tag{12}$$

From Eqs. (5) and (11), the electric power consumption per unit dewatered volume by electroosmosis W/Q_E is expressed as follows:

$$\frac{W}{Q_E} = \frac{1}{\varepsilon_{1w}}\left[\frac{\varepsilon_{1w}}{\varepsilon_{1w}(1 - \varepsilon_{2a}) - \varepsilon_{2w}(1 - \varepsilon_{1a})}\left\{\frac{1 - (\varepsilon_{1w} + \varepsilon_{1a})}{\lambda_2} - \frac{1 - (\varepsilon_{2w} + \varepsilon_{2a})}{\lambda_1}\right\}\frac{I_0^2}{2}t + \frac{H_0}{\alpha}I_0\right] \tag{13}$$

From Eqs. (5) and (12), the following approximate equation can be obtained in the case of sludge with large water content.
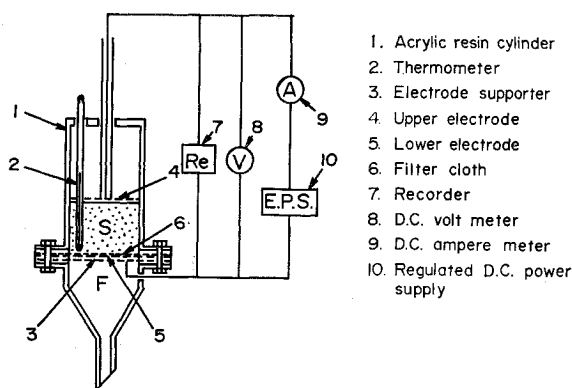
1. Acrylic resin cylinder
2. Thermometer
3. Electrode supporter
4. Upper electrode
5. Lower electrode
6. Filter cloth
7. Recorder
8. D.C. volt meter
9. D.C. ampere meter
10. Regulated D.C. power supply

Fig. 2 Schematic diagram of experimental apparatus

$$\frac{W}{Q_E}=\frac{1}{\varepsilon_{1w}}\left\{\frac{\varepsilon_{1w}}{\varepsilon_{1w}-\varepsilon_{2w}}\left(\frac{1-\varepsilon_{1w}}{\lambda_2}-\frac{1-\varepsilon_{2w}}{\lambda_1}\right)\frac{I_0^2}{2}t+\frac{H_0}{\alpha}I_0\right\}$$ (14)

Also, defining the dewatering efficiency η as the ratio of Q_E to the initial total water content of sludge, η is expressed as

$$\eta=\frac{Q_E}{AH_0\varepsilon_{1w}}=\frac{\alpha I_0}{\lambda_1 H_0}t$$ (15)

And the time till the end of electroosmotic dewatering t_e is expressed as Eq. (16) from the material balances of the liquid and the solid in the sludge bed at the end of dewatering.

$$t_e=\left[1-\frac{\{1-(\varepsilon_{1w}+\varepsilon_{1a})\}}{\{1-(\varepsilon_{2w}+\varepsilon_{2a})\}}\left(\frac{\varepsilon_{2w}}{\varepsilon_{1w}}\right)\right]\frac{\lambda_1 H_0}{\alpha I_0}$$ (16)

Neglecting ε_{1a} and ε_{2a}, t_e is approximately written as Eq. (17).

$$t_e=\left\{1-\frac{(1-\varepsilon_{1w})}{(1-\varepsilon_{2w})}\left(\frac{\varepsilon_{2w}}{\varepsilon_{1w}}\right)\right\}\frac{\lambda_1 H_0}{\alpha I_0}$$ (17)

Experimental Apparatus and Procedure

The outline of experimental apparatus is shown in **Fig. 2**. The lower electrode is set at the bottom of an acrylic resin cylinder ① with inner diameter of 90 mm. The electrode which is made of reticular copper or stainless steel of 20 mesh ⑤ is used as the lower one. The filter cloth (SP#7) ⑥ is set up in contact with the upper surface of lower electrode. The sludge is put in the portion S of cylinder and the upper electrode ④ is set up in contact with the surface of this sludge bed. The upper electrode is made of a perforated copper or carbon plate with hole diameter of 3 mm in order to remove the small amount of gas produced by electrolysis. As the height of sludge bed decreases with the dewatering of sludge, the position of the upper electrode is adjusted as always to be in contact with the upper surface of sludge bed. In this case, the sludge bed is not compressed by the upper electrode. Deionized water is used as the dispersion medium and the sludge used in this experiments is

Table 1 Properties of sludges

Kinds of sludge	Solid conc. of sludge [wt. %]	Initial height of sludge bed [cm]	Density of particle [g/cm³]	Polarity of ζ-potential
White clay	60.0	4.4	2.66	negative
Bentonite	20.0	2.7	2.59	negative
Magnesium hydroxide	50.0	3.7	2.23	positive

Initial water content of sludge is 200 [cm³], respectively.

Table 2 The fundamental values used for the calculation

Kinds of sludge	ε_{1w} [—]	λ_1 [1/Ω·cm]	α [cm²/volt·sec]
White clay	0.643	8.30×10^{-4}	5.10×10^{-5}
Bentonite	0.914	1.21×10^{-3}	3.91×10^{-5}
Magnesium hydroxide	0.707	7.43×10^{-4}	1.90×10^{-5}

adequately mixed. The polarity of both electrodes is determined in consideration of the polarity of ζ-potential of the particles, and then the electric fields under condition of constant electric current are applied to the sludge bed by a Regulated D. C. Power Supply ⑩. Immediately after the water starts to flow down in part **F** in Fig. 2, the total dewatered volume by gravitation and electroosmosis is measured with a burette. The voltage applied to the sludge bed is measured with an Automatic Recorder ⑦ at the same time. The dewatered volume by electroosmosis is obtained by subtracting the dewatered volume by gravitation from the total dewatered volume.

The kind of sludges and their properties used in this experiment are shown in **Tables 1** and **2**. The initial water content of sludge is nearly equal to the water content of sludge thickened by gravitational sedimentation.

The electroosmotic coefficient α is calculated from the equation $\alpha=q_E/A\varepsilon_{1w}E_{av}$. Here q_E is the flow rate of electroosmotic permeation obtained in the early period of measurement and E_{av} is the average strength of electric field in this period.

Experimental Results and Discussion

Effect of electroosmosis on dewatering of sludges at constant electric current

For white clay and bentonite sludges, the relation between the total dewatered volume Q_T and the dewatering time t is shown with the electric current density I_0 as parameter in **Fig. 3**. Q_T is the sum of the dewatered volume by gravitation Q_G and the dewatered volume by electroosmosis Q_E. It is clear that the total dewatering flow rate (dQ_T/dt) increases considerably with increasing I_0. It is noticed that the electroosmotic dewatering is very effective for bentonite sludge which is difficult to dewater by gravitation. The experimental results for $Mg(OH)_2$ sludge also

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Fig. 3 Relation between Q_T and t at constant electric current

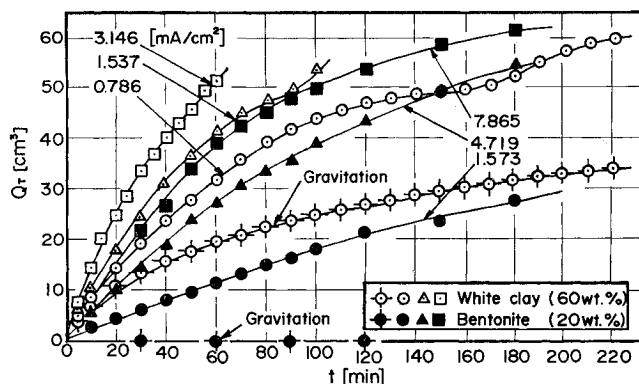Fig. 4 Relation between Q_E and t at constant electric current

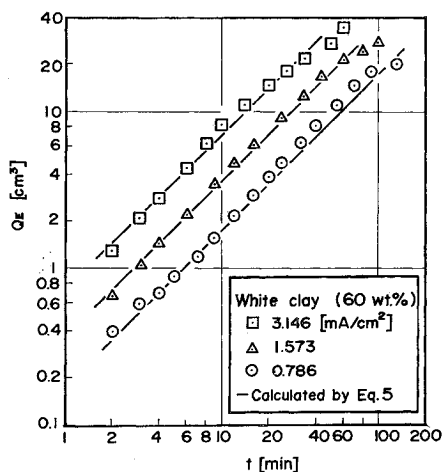Fig. 5 Relation between Q_E and t at constant electric current

Fig. 6 Relation between Q_E and t at constant electric current

show a similar tendency to that of white clay sludge. In the case of white clay, the bending points were found out at Q_T of about 50 cm³ in Fig. 3 and it was observed that the voltage applied to the sludge bed increased rapidly at that points under condition of constant electric current. This phenomenon can be considered that the porosity of water part in the sludge bed changes from ε_{1w} to ε_{2w} and the electric resistance of the sludge bed increases with changing the water content of sludge. That is to say, it may be considered that the first dewatering process is finished at the bending point and the secondary dewatering process immediately follows. It is observed that large electric power consumption is needed in the secondary dewatering process. The secondary dewatering process shows several complex phenomena in the sludge bed, such as a crack creation, temperature rising and drying by Joule's heat.

Comparison of experimental results with calculated results

Figs. 4, 5 and 6 show the relation between the dewatered volume by electroosmosis Q_E and the dewatering time t on log-log paper for each sludge with I_0
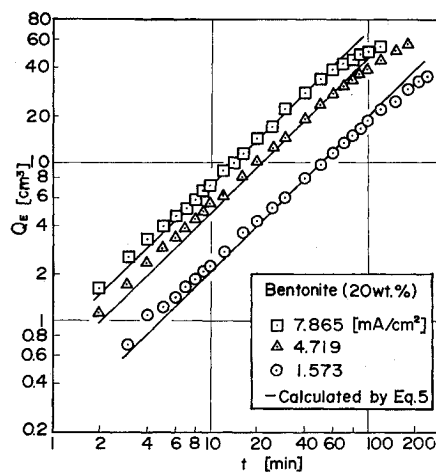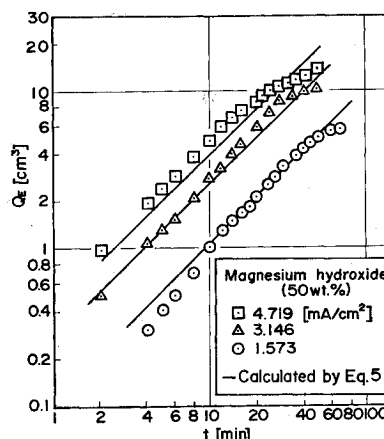
as parameter, and these figures show the comparison of the experimental results with the relationship expressed by Eq. (5). In these figures, each key shows the observed values and the solid lines express the theoretical results, respectively. The values calculated by Eq. (5) show a good agreement with the observed values within $\pm 20\%$ range except for the neighborhood of the end of dewatering.

The relation between the electric power consumption W and the dewatering time t is expressed by Eq. (12). Figs. 7 and 8 show the comparison of the experimental results with the values calculated by Eq. (12) with I_0 as parameter. The values of ε_{2w} and λ_2 used for the calculation of W by Eq. (12) were, respectively, obtained by measurement of porosity of water part and by calculation with Ohm's law using the voltage at the time when the first dewatering process had finished. Eq. (12) shows that W is a quadratic equation with respect to t. In the case of Mg(OH)$_2$ sludge, the experimental results coincide approximately with the theoretical equation for each I_0 as shown in Fig. 8. In
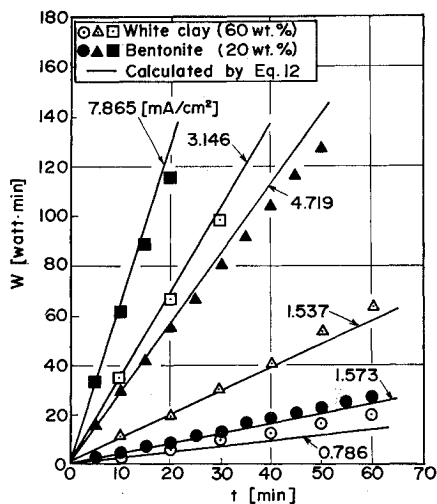
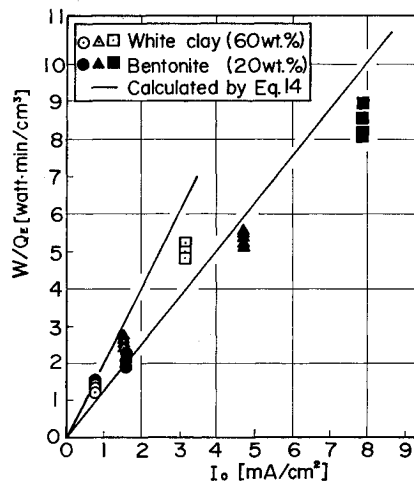Fig. 7 Relation between W and t at constant electric current

Fig. 9 Relation between W/Q_E and I_0 at constant electric current
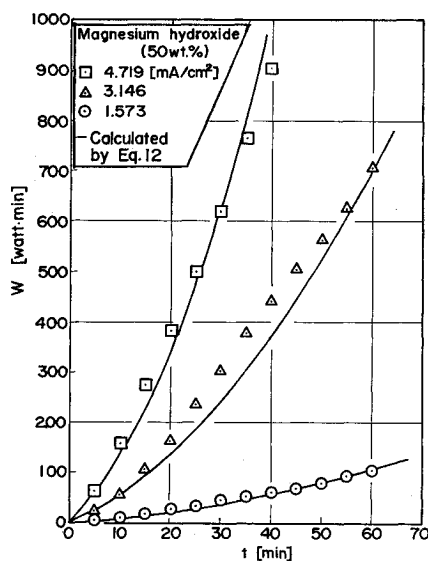

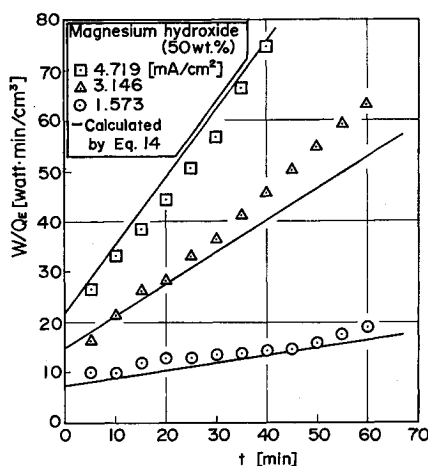Fig. 8 Relation between W and t at constant electric current

Fig. 10 Relation between W/Q_E and t at constant electric current

the cases of white clay and bentonite sludges, the relations between W and t are fairly linear for the experimental results as shown in Fig. 7 and the values calculated by Eq. (12) are in agreement with them. It is shown that these relations are approximately expressed as $W=(AI_0^2 H_0/\lambda_1)t$ because the quadratic term of t is much smaller than the linear term of t in Eq. (12). The difference in the relations between W and t in Figs. 7 and 8 is due to the following experimental results. In the case of $Mg(OH)_2$ sludge, the electric resistance of sludge bed increases gradually with t under condition of constant electric current. In the cases of white clay and bentonite sludges, their electric resistances almost never change with t. Therefore, it is found that the relation between W and t is influenced by the electrical characteristics of the sludge.

The relation between the electric power consumption per unit dewatered volume by electroosmosis W/Q_E and the dewatering time t or the electric current density I_0 is expressed by Eqs. (13) and (14). The comparison of the experimental results with the values calculated by Eq. (14) is shown in Figs. 9 and 10. In the cases of white clay and bentonite sludges as shown in Fig. 9, W/Q_E becomes independent of t because both Q_E and W are linear with respect to t as shown in Figs. 4, 5 and 7, therefore W/Q_E is related to only I_0. The values of W/Q_E obtained experimentally are a linear function of I_0 irrespective of t and show a similar tendency to the values calculated by Eq. (14). According to Eq. (14), W/Q_E is a quadratic equation with respect to I_0. However, Eq. (14) can be expressed approximately as $W/Q_E=(H_0/\varepsilon_{1w}\alpha)I_0$ when the quadratic term of I_0 is much smaller than the linear term of I_0. As to the experimental results of these sludges, it is found that Eq. (14) is nearly expressed by the linear relationship in respect of I_0.

When the quadratic term of I_0 in Eq. (14) can not be neglected, W/Q_E is linear in respect of t as shown in Eqs. (13) and (14). In the case of Mg(OH)$_2$ sludge, W/Q_E is expressed as a linear function of t as shown in Fig. 10. It is found that the slopes of straight lines increase with increasing I_0 and that the value of W/Q_E at $t=0$ shows $H_0 I_0/\varepsilon_{1w}\alpha$ in Eq. (14). Therefore, the electric power per unit dewatered volume by electroosmosis increases with increasing I_0, namely the electric power efficiency decreases with an increase of I_0. This fact must be noticed in the case of carrying out electroosmotic dewatering.

The time till the end of electroosmotic dewatering t_e is expressed by Eq. (17). As an example, t_e calculated by Eq. (17) under condition of constant electric current density of 1.573 mA/cm^2 is 113 min for white clay, 264 min for bentonite, and 51 min for Mg(OH)$_2$, respectively. These calculated values coincide nearly with the observed values in Figs. 4, 5 and 6. Therefore Eq. (17) is regarded as appropriate.

From the above results, the electroosmotic dewatering mechanism of sludge can be explained by the model of electroosmotic flow through the particle packed bed and it was confirmed that the equations obtained by theoretical analysis were appropriate.

Conclusion

An electroosmotic phenomenon can be used to dewater sludge. A fundamental study on the electroosmotic dewatering of compressible sludge under condition of constant electric current was performed experimentally and theoretically by using the model of electroosmotic flow through the particle packed bed. The following results were obtained.

1) In the electroosmotic dewatering of white clay, bentonite and magnesium hydroxide sludges under constant electric current, the dewatering flow rate and the dewatered volume are increased being proportional to the electric current density. Especially, the electroosmotic dewatering is very effective for a gelatinous sludge such as bentonite which is difficult to dewater mechanically.

2) The electroosmotic dewatering mechanism of compressible sludge can be explained by the model of electroosmotic flow through a particle packed bed. It was confirmed that the equations obtained by theoretical analysis were appropriate for the design of elec-

troosmotic dewatering apparatus.

Nomenclature

A	= dewatering area or area of electrodes	[cm^2]
D	= dielectric constant of liquid	[C.G.S.e.s.u.]
E	= strength of electric field in sludge bed	[volt/cm]
H	= height of sludge bed	[cm]
H_0	= initial height of sludge bed	[cm]
H_t	= total height of sludge bed at time t	[cm]
I_0	= electric current density	
		[amp/cm^2] or [mA/cm^2]
Q_E	= dewatered volume by electroosmosis	[cm^3]
Q_G	= dewatered volume by gravitation	[cm^3]
Q_T	= total dewatered volume by gravitation and electroosmosis	[cm^3]
q_E	= electroosmotic flow rate	[cm^3/sec]
t	= dewatering time	[sec] or [min]
t_e	= time till the end of dewatering	[sec]
u_E	= electroosmotic velocity	[cm/sec]
V	= partial voltage applied to sludge bed	[volt]
V_t	= voltage applied to entire sludge bed at time t	[volt]
W	= electric power consumption	
		[watt·sec] or [watt·min]
α	= electroosmotic coefficient defined as Eq. (3)	[cm^2/volt·sec]
ε_a	= porosity of air part in sludge bed	[—]
ε_w	= porosity of water part in sludge bed	[—]
ζ	= ζ-potential of particles	[volt]
η	= dewatering efficiency defined as Eq. (15)	[—]
κ	= factor of particle shape	[—]
λ	= equivalent specific conductivity of sludge bed	[1/Ω·cm]
μ	= viscosity of liquid	[g/cm·sec]

⟨Subscripts⟩

1	= value for dewatering sludge bed	
2	= value for dewatered sludge bed	

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