CONTINUOUS AND INTERRUPTED ELECTROOSMOTIC DEWATERING OF CLAY SUSPENSIONS

by

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<u>In the name of God</u>

To

my dear parents

and my beloved wife

ABSTRACT

Suspensions of Bentonite, kaolin and red clay were dewatered electroosmotically under continuous and interrupted DC voltage and current. The suspension was held in a vertical 5-cm diameter column between two platinum mesh electrodes, an upper anode and a lower cathode. Suspensions were prepared with $CaCl_2$ in distilled water at concentrations up to 10^{-2} M. The initial solid content was between 9.1 and 15 wt% for Bentonite and between 25 and 45 wt% for kaolin and red clay. The initial bed height ranged from 0.5 to 2 cm. Constant voltages from 2.75 to 5.0 V and constant currents from 30 to 90 mA were used. In the interrupted regime the off-time ranged from 0.5 to 20 s with the on-time fixed at 30 s. A short circuit or an open circuit was applied during the off-time. The interrupted process with a short circuit was also applied at the end of a DC run when dewatering had stopped.

Electroosmosis removed 20-70% of the water with an energy expenditure well below the heat of vaporization. The water removal rates were increased by the addition of $CaCl_2$. Beds of 0.5 cm thick were dewatered faster and with less energy consumption than thicker beds. Interruption with a short circuit applied during a 0.5 s off-time removed about 20-40% more water than DC for equal energy consumption. Interruption at the end of a DC run removed nearly the same amount of water as interruption applied from the beginning of a run. Relative motion between the electrodes in the form of rotation of the upper electrode at 40 or 70 rpm had no significant effect on dewatering. The Helmholtz/Smoluchowski theory did not agree with the experiment results for the effects of interruption in power and electrolyte content.

Résumé

Les solutions de Bentonite, de kaolin et d'argile rouge sont asséchées électroosmotiquement sous un voltage et un courant continu et alternarif. La solution est maintenue dans une colonne vertical de 5 cm de diamètre, entre deux électrodes de platine: l'anode supérieure et la cathode inférieure. Les solutions sont préparées a partir de $CaCl_2$ dans l'eau distillée a des concentrations allant jusqu' à 10^{-2} Mol/l. L'échantillon solide initial contient entre 9.1% et 15% en poids de Bentonite et entre 25% et 45% en poids de kaolin et d' argile rouge. La hauteur initiale du lit varie de 0.5 a 2 cm. Des voltages constants de 2.75 à 5.0 V furent utilisés ainsi que des courants constants de 30 à 90 mA. En régime discontinue, la période de non-fonctionnement varie de 0.5 a 20 s lorsque la période de fonctionnement est fixée à 30 s. Un court-circuit ou un circuit ouvert est appliqué pendant la période de non-fonctionnement. Un court-circuit est également appliqué pour interrompre le processus a la fin d'une expérience DC lorsque l'asséchement est stoppé.

L'electroosmose retire 20 a 70% d'eau avec une dépense d'énergie très inférieure a la chaleur de vaporisation. Le pourcentage d'eau retirée est amélioré par addition de $CaCl_2$. Les lits d'épaisseur 0.5 cm sont asséchés plus rapidement et avec une consommation d'énergie moindre que les lits plus épais. L'interruption du processus par un court-circuit appliqué pendant 0.5 s retire 20 à 40% d'eau supplémentaire que le DC pour une même consommation d'énergie. L'interruption à la fin d'une expérience DC enlève pratiquement la même quantité d'eau que l'interruption appliquee au debut de l'expérience. Le mouvement relatif des électrodes, sous forme de rotation de l' électrode supérieure à 40 ou 70 tr/mn n'a pas d'effet significatif sur l'assechement. La théorie Helmholtz/Smoluchowski est en desaccord avec les resultats des experiences en ce qui concerne les effets de coupure de courant et de composition de l'électrolyte.

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CHAPTER 1

INTRODUCTION

Separations are essential to most manufacturing operations in processing industries throughout the world. The cost of a given separation method is often a major factor in the manufacturing cost of a product. The cost of separation is related to the equipment needed, the energy required, and the time required to effect the separation. There are many critical areas of technology in which the application of separation is crucial. In some industries, it is necessary to separate fine particles from an aqueous suspension. These suspensions occur in a diverse range of activities, for example in coal preparation, sand washing, and mineral processing; in the chemical, electrochemical, metallurgical and manufacturing industries; textiles, animal products, agricultural, and food processing activities; in water purification and in municipal and industrial waste treatment. It is often necessary to concentrate dilute suspensions and then to consolidate the resulting sediment for sale or for safe disposal.

1.1 Solid-Liquid Separation Methods

The relationship between achievable moisture content as a function of particle size is illustrated in Fig. 1-1. This Figure shows the range of application of various solid-liquid separation techniques. The particle size/percent liquid space may be divided roughly into two regions by the diagonal line superimposed on the figure. Upward to the right of the line the applicable methods involve hydraulic dewatering, i.e. the movement of water through the suspension caused by a pressure gradient.

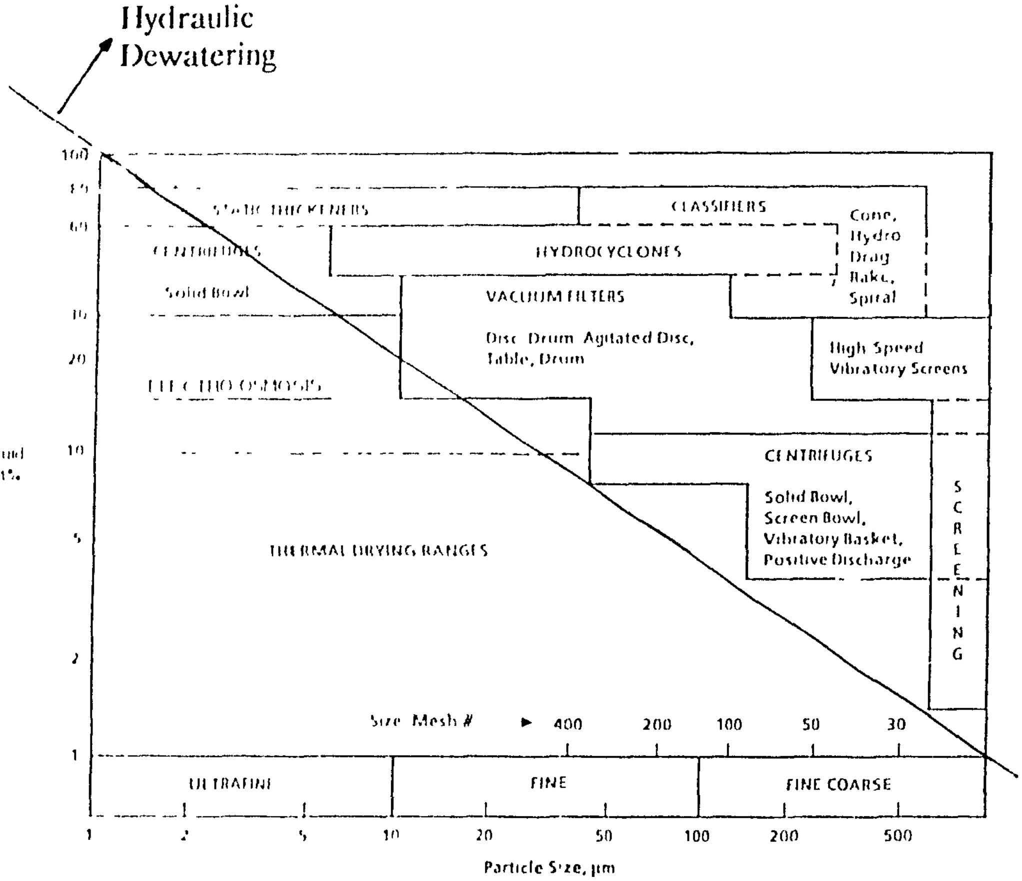


Figure 1.1 Range of application of various dewatering methods as a function of moisture content and particle size, [Grant, C.S., 1989]

The region below and to the left of the diagonal line is the difficult to dewater region. Here, thermal dewatering (evaporation or drying) and, to lower extent, electroosmotic dewatering, are the preferred methods.

In a number of dewatering operations, thermal drying is implemented as the final step. Although thermal drying processes require short times, they often require uneconomically large amounts of energy Electroosmosis may be used for ultrafine particles and, possibly, for heat sensitive materials which may not be dried thermally. Electroosmotic dewatering utilizes the surface charges which prevent fine particles from agglomerating and are responsible for the inherent stability of colloidal suspensions. There is the potential to remove water with smaller amounts of energy than are required for vaporization.

1.2 Electrokinetic Separation

Electrokinetic phenomena involve electric fields tangential to a charged interface and tangential movement of the phases along the phase boundary. These phenomena may arise either through the application of an external electric field, resulting in movement, or through the mechanical movement of one of the phases, resulting in the generation of an electric field. In most practical applications of electrokinetics external fields are applied, resulting in electrophoresis and electroosmosis.

Electrophoresis relates to the movement of solids, usually particles, through a relatively stationary fluid, while electroosmosis relates to the movement of fluid through a porous medium whose surface has an electrical double layer When such relative motion occurs, the few layers of fluid immediately adjacent to the solid are immobile with respect to the solid, and a "slipping plane" exists, some distance away from the interface. In aqueous systems, the immobile fluid is generally considered to be composed of oriented dipoles The potential at the slipping plane is called the zeta potential The zeta potential, and thus the electroosmotic effect, can be modified by the addition of flocculants, dispersants, and ionic solutions of various kinds. Generally, The zeta potential of particles dispersed in water is in the -100 to +100 millivolt range.

1.3 Models of Electroosmosis

The classical model of electroosmosis is the Helmholtz/Smoluchowski theory. It assumes that an electric field is applied along the axis of a capillary whose walls carry an electric double layer. Under the influence of the field, the ions in the diffuse layer near the shear plane move toward one electrode and carry liquid with them. The Helmholtz/Smoluchowski theory, originally developed for a straight cylindrical capillary, is based on the following assumptions (Ellis, 1976 and Hiemenz, 1986):

1. The radius of the capillary is much larger than the thickness of the electrical double layer. This is conventionally written as:

$$K R > 100 \qquad (1\text{-}1)$$

where K^{1} is the Debye thickness and R is the capillary radius.

2. The walls of the capillary are nonconducting.

3. The fraction of the current carried by ions in the double layer is negligible (i.e. negligible surface conductance).

The velocity outside the double layer is uniform and is given in SI units by:

$$u_e = \frac{-\zeta\ \varepsilon\ \epsilon_0}{\eta\ \lambda} \left(\frac{i}{a}\right) \tag{1-2}$$

where ε- dielectric constant of the bulk fluid

ζ- zeta potential (V)

ϵ_0- permittivity of free space $(8.85x10^{-12}\ A^2\ s^4\ /\ kg\ m^3)$

η- viscosity of the fluid (kg/m.s)

λ- specific conductance of the bulk fluid (S/m)

i- electric current (A)

a- cross sectional area of the capillary (m^2)

Since the field strength, E, and the current are related by:

$$E = \frac{i}{\lambda\ a} \tag{1-3}$$

Equation (1-3) can be written :

$$u_e = \frac{-\zeta\ \varepsilon\ \epsilon_0\ E}{\eta} \tag{1-4}$$

Electroosmotic transport in a porous material is carried out by applying voltage across a bed or "plug". The applied field E_a is given by

$$E_a = \frac{V_1 - V_2}{H} \tag{1-5}$$

Smoluchowski showed that eq. (1-1) applies to a porous material composed of nonconducting particles in a liquid medium if u_e is defined as the cross section average velocity of the fluid (i.e. the superficial velocity or the volumetric flux density). For a porous material:

$$u_e = \frac{-\zeta\ \varepsilon\ \epsilon_0}{\eta\ \lambda}\left(\frac{i}{A}\right) \tag{1-6}$$

where A is the cross sectional area of the porous plug and λ is the conductance of the bulk liquid in the pores. If Q is the volume of water removed from the porous material by electroosmosis, then:

$$u_e = \frac{1}{A}\frac{dQ}{dt} \tag{1-7}$$

The relationship between i/A and the strength of the applied field, E_a , depends upon the void fraction, which is assumed to be completely filled with liquids, and the structure of the porous material. The relationship between u_e and E_a may be written:

$$u_e = \frac{-\zeta\ \varepsilon\ \epsilon_0\ E_a}{\eta} f(\epsilon_w) \tag{1-8}$$

where $f(\epsilon_w)$ is a function of the void fraction, ϵ_w. This function has been determined for several model structures. For example, if a porous plug of length H contains straight cylindrical pores of length H, $f(\epsilon_w) = \epsilon_w$. O'Brien (1986) showed that $f(\epsilon_w) = 0.343$ for a porous material composed of uniform spheres in a simple cubic array where $\epsilon_w = 0.476$.

Electroosmosis is attractive as a method of dewatering because eq. (1-6) indicates that the rate of water removal is not a function of the water content (or void fraction). This equation and eq. (1-8) are subject to the assumptions listed above. The most important of these is that the pore radii are much larger than the thickness of the double layer.

Yukawa and colleagues (1978) developed a model of electroosmotic dewatering in which a voltage is applied to a sludge bed and the water is moved downward with the electroosmotic velocity u_e . They assumed that the sludge bed contained two layers: an upper dewatered layer and a lower layer which has the same water content as the original bed. Weber, Witwit and Mujumdar (1987) derived a simpler model by assuming that the bed dewatered uniformly. Both models were based upon eq. (1-6).

1.4 Experiments on Electroosmotic Dewatering

A number of studies has been reported for electroosmotic dewatering of fine particle suspensions. Only those related to the dewatering of clays are reviewed here. Because of their fine particle size and small pore structure, clays are particularly amenable to dewatering by electroosmosis.

Yoshida et al. (1985) dewatered gelatinous Bentonite suspensions under conditions of constant voltage and constant current. The apparatus was similar to that described in Chapter 2. The diameter of the bed was 7.2 cm and its initial height was 5.4 cm. Using their value for density of the bentonite particles, 2.767 g/cm, the initial volume fraction of water was 0.917. In constant voltage runs, four voltages were applied: 2.5, 5, 10 and 15 V. At 10 V and above, the current rose to a maximum and then fell dramatically. For lower voltage, the current was relatively constant. The largest applied voltage did not remove the most water. There was an optimum for voltage at which the water removed was a maximum (26% removal). In constant current runs, three currents were used. 50, 100 and 200 mA. In all cases, the voltage fell slowly as water was removed and then increased rapidly near the end of the run.

Lockhart (1983a, b, c) studied the electroosmotic dewatering of sodium kaolinite suspensions to determine the influence of voltage, salt content, pH, clay type and electrode material In most runs the initial solid content was 18 wt%. His apparatus was also similar to that described in Chapter 2. He began with a constant voltage, but when dewatering essentially stopped, the voltage was increased to a higher value which was maintained until the dewatering rate fell off again and the procedure was repeated A typical sequence was 2 V, 3 V, 25 V and 50 V. The suspensions were made with water and with NaCl and HCl at concentrations from 10^{-3} to 10^{-1} M. Salt or acid concentrations up to about 10^{-2} M usually allowed dewatering to proceed at lower voltages or permitted more complete dewatering at the same voltages, than suspensions prepared with water. Lockhart found that the water flow per unit of charge passed through the bed was not inversely proportional to the concentration of ions, nor was it proportional to the zeta potential. These conclusions are largely contrary to the theory outlined in the previous section.

Ju, Weber and Mujumdar (1991) worked on gelatinous Bentonite suspensions under conditions of constant DC voltage and constant DC current in a 5 cm diameter column The apparatus was also similar to that described in Ch. 2. The suspensions were prepared with $CaCl_2$ in distilled water at concentrations up to 1 M. The initial solid content was between 9.1 and 26 wt% and the initial bed height ranged from 1.0-5.2 cm. Constant voltages from 4-8 Volt and constant currents from 90-110 mA were used. Electroosmosis removed 20-60 % of the water, with energy expenditures well bellow the energy required to vaporize the water. With a constant initial field strength the smallest bed height (1 cm) gave the lowest energy of dewatering and the highest water flux per unit charge. The driest final bed, however, was obtained at a bed height of 2.1 cm. The initial solid content had little effect on the final average solid content. The water removal rate and the final solid content increased with the addition of $CaCl_2$. The Helmholtz/Smoluchowski theory did not agree with the experimental results for the effects of electrolyte concentration and bed height.

If the initial bed height does not affect the rate of dewatering and the water flux per unit charge (based on the Helmholtz/Smoluchowski theory), a thin bed should dewater to a given solid content faster than a thick bed In addition, less energy per unit mass of solid material should be consumed by thin beds because the use of low voltages results in less gas production and Joule heating These proposals were put forward in a report by New Brunswick Research and Productivity Council (published by Canadian Electrical Association, 1989). They suggested the use of thin beds (small electrode spacing) so that current would flow for reasonably small applied voltages, even when little water was left.

Yankovskii, Khrustalev and Zavialova (1989) dewatered peat electroosmotically with a pulsed electric field in an apparatus similar to that described in Chapter 2. They used rectangular voltage signals with frequencies between 0.25 and 20 kHz. The initial field was 1 to 3 V/cm. They found that pulsation removed more water than DC operation at the same voltage.

Continuous machines for electroosmotic dewatering have relative motion between the electrodes. Electrodes are constructed as belts, drums or screws to meet the requirements for continuous feed and continuous cake removal Some examples are shown in Fig. 1-2. Coackly of the Motherwell Bridge and Engineering Company Limited (U.K.) patented a machine based on the screw-like motion of rotating helical blades (see Fig. 1-2a). A moving double-belt apparatus for electroosmotic dewatering

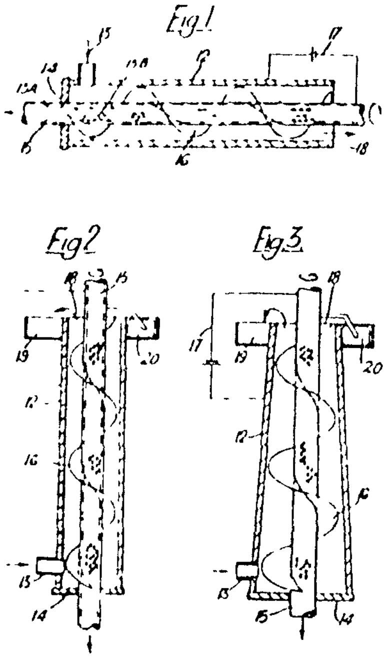


Figure 1-2a From a patent by Coackley. 12: Outer casing and anode. 15: Hollow cathode. 16: Helical blade.

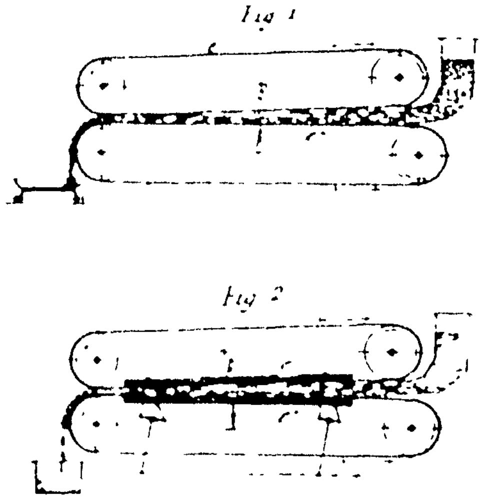


Figure 1-2b From one of many patents issued to Botho Schwerin.

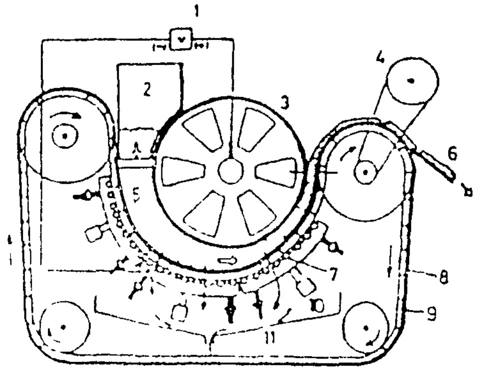


Figure 1-2c Fuji electric machine. 1: DC power supply. 2: Hopper. 3: Drum (anode). 4: Driving means. 5: Sludge. 6: Discharged sludge. 7: Roller. 8: Filter cloth. 9: Caterpillar (cathode). 10: Water. 11: Basin.

Figure 1-2 Machines for electroosmotic dewatering (from a report prepared by New Brunswick Research Productivity Council, published by Canadian Electrical Association, 1989) was designed by Schwerin (see Fig. 1-2b). Figure 1-2c shows a device based on a revolving drum and a moving belt. In all cases the suspension move between the two electrodes. Both electrodes may move in the same direction, as in Figs 1-2b and c, or one electrode may be stationary as in Fig. 1-2a.

1.5 Objectives

The theory reviewed above suggests that the following variables affect electroosmotic dewatering:

-the zeta potential of the particles

-the current or voltage

-the conductivity of the suspension

Previous experiments on electroosmotic dewatering indicate that the following additional variables may be important:

-the initial height of the bed before dewatering

-the relative motion between electrodes

-the type of the input power (DC, Interrupted voltage or current,...)

-the content of electrolyte in the water in the suspension

-the initial solid content of the suspension

The main objectives of this thesis were:

1. to measure rates of electroosmotic dewatering under interrupted power and to compare them to rates for DC
2. to determine the effect of initial bed height with emphasis on small heights
3. to determine the effect of relative motion between the electrodes on DC electroosmotic dewatering.

1.6 Variables

Bentonite clay was used in most of the experiments because water will not drain by gravity from suspensions containing as little as 10 wt% solid. In addition, earlier studies are available for Bentonite and other clays. A few runs were done with kaolin and red clay to extend the results. The electrolyte used in the present work was $CaCl_2$. Relative motion between the electrodes was provided by rotating one of two parallel electrodes.

The independent variables in the study were:

- $CaCl_2$ concentration in the water used to prepare the suspension
-original solid content
-original bed height
-rotation speed of the upper electrode
-current (in constant current experiments) or voltage (in constant voltage experiments)
-frequency and percentage of interrupted voltage or current

The following dependent variables were measured as functions of time:

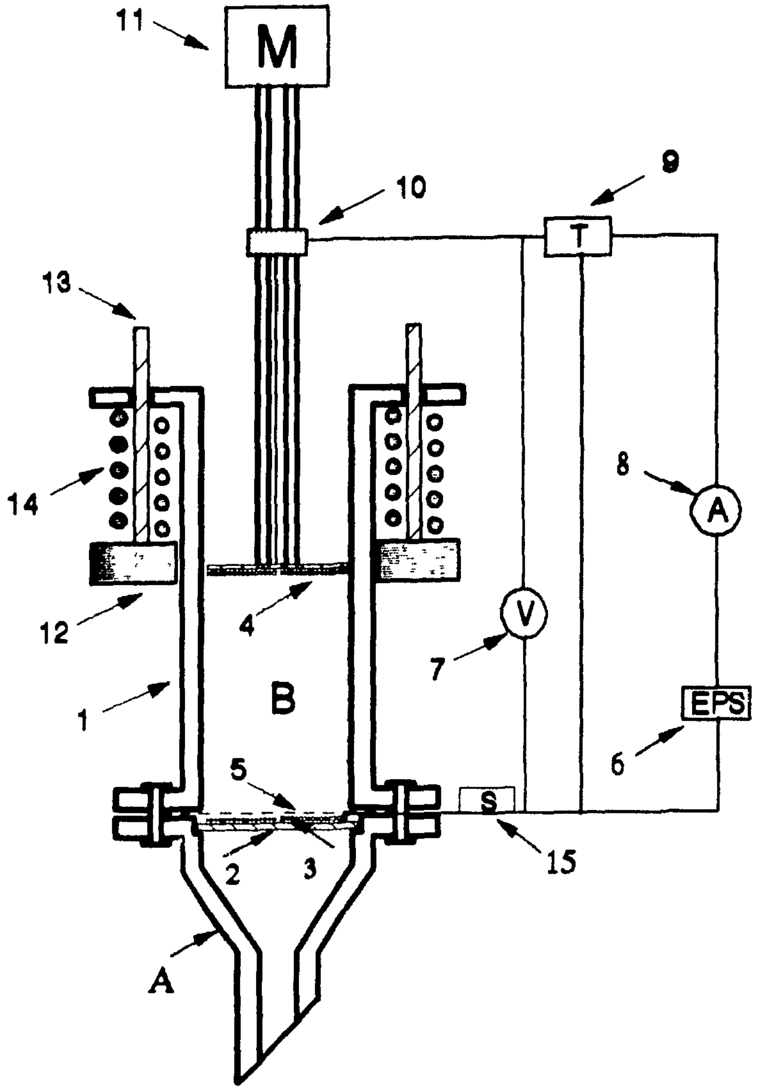
-volume of water removed
-overall voltage drop (in constant applied current experiments)
-current (in constant applied voltage experiments)
-output voltage from a resistance in the circuit to measure the variation of current during each cycle of interrupted operation (see Fig. 2-1)

CHAPTER 2

EXPERIMENTAL METHODS AND MATERIALS

2.1 Experimental Apparatus

A schematic diagram of the electroosmotic dewatering apparatus is shown in Fig. 2-1. The suspension was held in a vertical acrylic cylinder (1), 5 cm ID and 20 cm long, with flanges on the lower end. A flanged funnel-shaped base (A) was bolted to the lower flange. The base (A) held a drilled acrylic cylindrical plate (2) to support the lower electrode (3). This support had 90 holes of 3 mm diameter drilled on a square pattern with 4.8 mm between centres. The plate was 63 mm in diameter and 7 mm thick. An electrical wire was soldered to the edge of the lower electrode and passed through a small channel on the top of base (A). A filter sheet (5) above the lower electrode was held in place by an O-ring clamped between the two lower flanges. The filter sheet, which was made of Nylon with 5.0 μm pore size, was supplied by Micron Separation Inc (Westborough, MA). An acrylic cylindrical plate with 29 holes of 2 mm diameter drilled through it and distributed to match the diamond pattern of opening in the electrode was fixed to the end of a hollow shaft. The upper electrode (4) was attached to this plate The shaft was linked to the shaft of a motor (11). An electrical wire, which passed through the hollow shaft, was soldered to the upper electrode and was connected to the circuit by a slip ring (10) on the shaft. The vertical cylinder and the lower part of the apparatus were moved upward slowly during dewatering by two weak springs (14) to make contact between the bed and the upper electrode. The springs were chosen so that there was no



1. Acrylic resin cylinder
2. Bed support
3. Lower electrode
4. Upper electrode
5. Filter paper
6. DC power supply
7. Voltmeter
8. Ammeter
9. Timer Relay
10. Contactor
11. Motor
12. Support
13. Metallic Rod
14. Spring
15. Shunt

Figure 2-1 Electroosmotic dewatering apparatus significant compression of the bed.

Each electrode was a circular piece of titanium mesh coated with platinum to a thickness of 2.5 μm to prevent electrode corrosion. The wires forming the mesh were flattened in cross section. The openings in the mesh were diamond-shaped and the open area was about 50% of the total cross section. These electrodes were supplied by Engelhard Corporation USA (Edison, NJ). Since the Bentonite, kaolin and red clay had negative charges, the upper electrode was made the anode so that water migrated downward.

A constant voltage or a constant current was applied to the electrodes by a regulated DC power supply (6). The interrupted voltage and current were provided by a Timer Relay (9) with a suitable circuit for different types of interrupted electroosmotic dewatering. Voltage and current were measured as functions of time using voltmeters (7) and ammeter (8). The variation of the current during each cycle of the interrupted experiments was recorded from the screen of a Storage Oscilloscope by a Shunt (15) with 0.2 Ω resistance.The water removed by electroosmosis was collected in a graduated cylinder (not shown in Fig. 2-1) held below the funnel (A). The volume of water was measured as a function of time.

2.2 Experimental Variables

The independent variables were:

1. initial height of bed (H_0)
2. magnitude of the constant applied DC voltage (V_0) or the constant applied DC current (i)
3. the time intervals of the interrupted voltage or current (t_1/t_2)

4. rotation speed (Ω)

5. concentration of $CaCl_2(C_0)$ in the distilled water used to prepare the Clay suspension

6. initial solid content of the suspension (S_0)

In interrupted dewatering a constant current or voltage is applied for t_1 seconds followed by a period of t_2 seconds when the power supply is turned off. The pattern is repeated throughout dewatering During off-period there is either a short circuit or an open circuit. Interrupted electroosmotic dewatering with a short circuit is denoted "IS"; with an open circuit, "IO".

For experiments with Bentonite the experimental conditions are listed in Table 2-1 for constant DC current, in Table 2-2 for interrupted current and in Table 2-3 for constant and interrupted voltage. The experimental conditions for kaolin and red clay are presented in Table 2-4.

2.3 Properties of Materials

Purified grade Bentonite powder was supplied by Fisher Scientific Co. (Pittsburgh, PA). Laboratory grade kaolin powder was supplied by A & C American Chemicals Ltd. (Montreal, PQ) Airfloated red clay was supplied by Cedar Height Clay Co. (Ohio). The typical chemical analysis of Bentonite, kaolin and red clay is presented in Table 2-5. These materials contain largely silica and alumina with smaller amounts of the oxides of potassium, titanium, iron, magnesium, calcium and sodium.

The particle size distributions of the materials were measured with a Malvern 2600 Particle Sizer (Malvern Instruments, Malvern, England). Figures 2-2a through

Table 2-1 Experimental conditions for Bentonite under constant current

$CaCl_2$ concentration M	current mA	initial bed height cm	initial solid content wt%	rotation speed rpm
0	90	2.0	9.1	0
0	90	1.0	9.1	0
0	90	0.5	9.1	0
10^{-2}	90	2.0	9.1	0
10^{-2}	90	1.0	9.1	0
10^{-2}	90	0.5	9.1	0
10^{-2}	30	1.5	9.1	0
10^{-2}	30	1.5	9.1	40
10^{-2}	30	1.5	9.1	70
10^{-3}	50	1.0	9.1	0
10^{-3}	50	1.0	9.1	40
10^{-3}	50	1.0	9.1	70

Table 2-2 Experimental conditions for Bentonite under interrupted current

$CaCl_2$ concentration M	current mA	initial bed height cm	initial solid content wt%	type of the process	time intervals s/s
10^{-2}	30	1.5	9.1	IS	30/0.5
10^{-2}	30	1.5	9.1	DC - IS	--- - 30/0.5

Table 2-3 Experimental conditions of constant & interrupted voltage for Bentonite

$CaCl_2$ concentration M	voltage V	initial bed height cm	initial solid content wt%	type of the process	time intervals s/s
0	5.5	2.0	9.1	DC	---
0	5.5	2.0	9.1	IS	30/0.5
0	5.5	2.0	9.1	IO	30/0.5
0	4.13	1.5	9.1	DC	---
0	4.13	1.5	9.1	IS	30/0.5
0	2.75	1.0	9.1	DC	---
0	2.75	1.0	9.1	IS	30/0.5
0	2.75	1.0	9.1	IO	30/0.5
0	2.75	1.0	9.1	IS	30/3
0	2.75	1.0	9.1	IS	30/20
10^{2}	2.75	1.0	9.1	DC	---
10^{2}	2.75	1.0	9.1	IS	30/0.5
10^{2}	2.75	1.0	9.1	DC - IS	--- - 30/0.5
10^{2}	2.75	1.0	15.0	DC	---
10^{2}	2.75	1.0	15.0	IS	30/0.5

Table 2-4 Experimental conditions under constant and interrupted voltage for kaolin & red clay

$CaCl_2$ concentration M	voltage V	initial bed height cm	initial solid content wt%	type of the process	time intervals s/s	material
0	5.0	1.0	25.0	DC	---	Kaolin
0	5.0	1.0	25.0	IS	30/0.5	Kaolin
0	5.5	1.0	45.0	DC	---	Red Clay
0	5.5	1.0	45.0	IS	30/0.5	Red Clay

Table 2-5 Typical chemical analysis of Bentonite, kaolin and red clay in weight percent

	Bentonite	Kaolin	Red clay
Silica (SiO_2)	65.9	44.00	64.27
Alumina (Al_2O_3)	17.6	40.00	16.41
Iron Oxide (Fe_2O_3)	4.1	0.20	7.04
Titania (TiO_2)	0.2	1.00	1.06
Magnesia (MgO)	2.4	0.20	1.55
Calcium Oxide (CaO)	1.3	0.05	0.23
Sodium Oxide (Na_2O)	2.3	0.30	0.40
Potassium Oxide (K_2O)	0.3	0.04	4.07

2-2c show the volumetric size distributions of the Bentonite, kaolin and red clay, respectively. Fifty percent of the Bentonite particles were smaller than 6.8 μm. The specific surface area was 1.15 m^2/cm^3 Fifty percent of kaolin particles were smaller than 46 μm and for red clay were smaller than 17 μm. The specific surface area of kaolin was 0.3 m^2/cm^3 and it was 0.62 m^2/cm^3 for red clay. The mean diameters of Bentonite, kaolin and red clay, D(4,3), derived from the volume distributions were 8.2 μm, 80.6 μm and 23.0 μm, respectively, where

$$D(4,3) = \left[\frac{\int_{D_0}^{D_m} D^4\, n(D)\, dD}{\int_{D_0}^{D_m} D^3\, n(D)\, dD} \right] \qquad (2\text{-}1)$$

The zeta potentials of the kaolin and red clay were measured with a Particle Micro-electrophoresis Apparatus Mark II (Rank Brothers, United Kingdom). The zeta potential data for Bentonite as measured by Ju (1990) are shown in Fig. 2-5. The pH was adjusted by the addition of 1 M HCl or 1 M NaOH. The zeta potential was negative for pH > 2 and decreased with increasing pH. Two values were obtained for suspensions prepared with aqueous $CaCl_2$. The zeta potential increased from -34 mV in a salt-free suspension to -14 mV when the suspension was prepared with 10^{-2} M $CaCl_2$. When the concentration of $CaCl_2$ was 10^{-1} M, the particles coagulated rapidly and sedimentation was so fast that the particle mobility could not be measured. At pH < 2, the same phenomena occurred. The zeta potentials of kaolin and red clay suspensions prepared in distilled water were -42 mV and -54 mV, respectively.

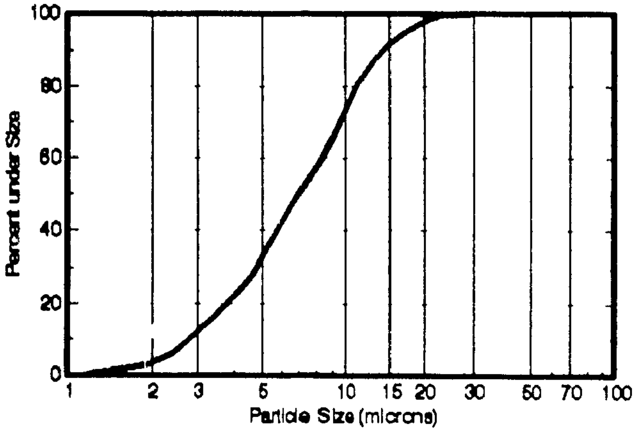


Figure 2-2a Particle size distribution of Bentonite

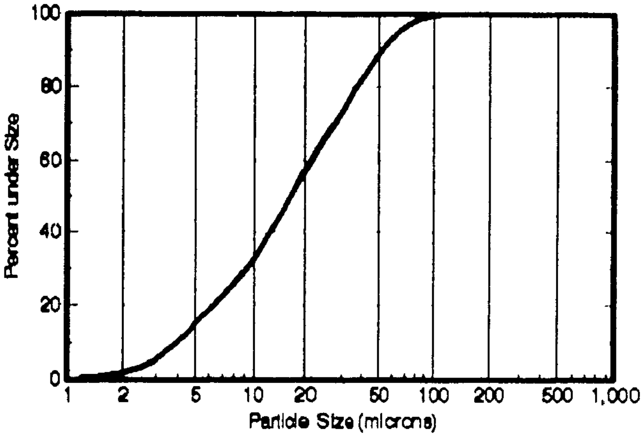


Figure 2-2b Particle size distribution of red clay

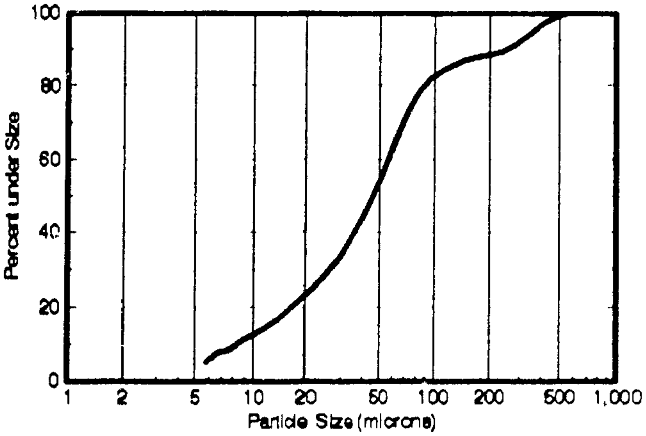


Figure 2-2c Particle size distribution of kaolin

Figure 2-2 Particle size distribution

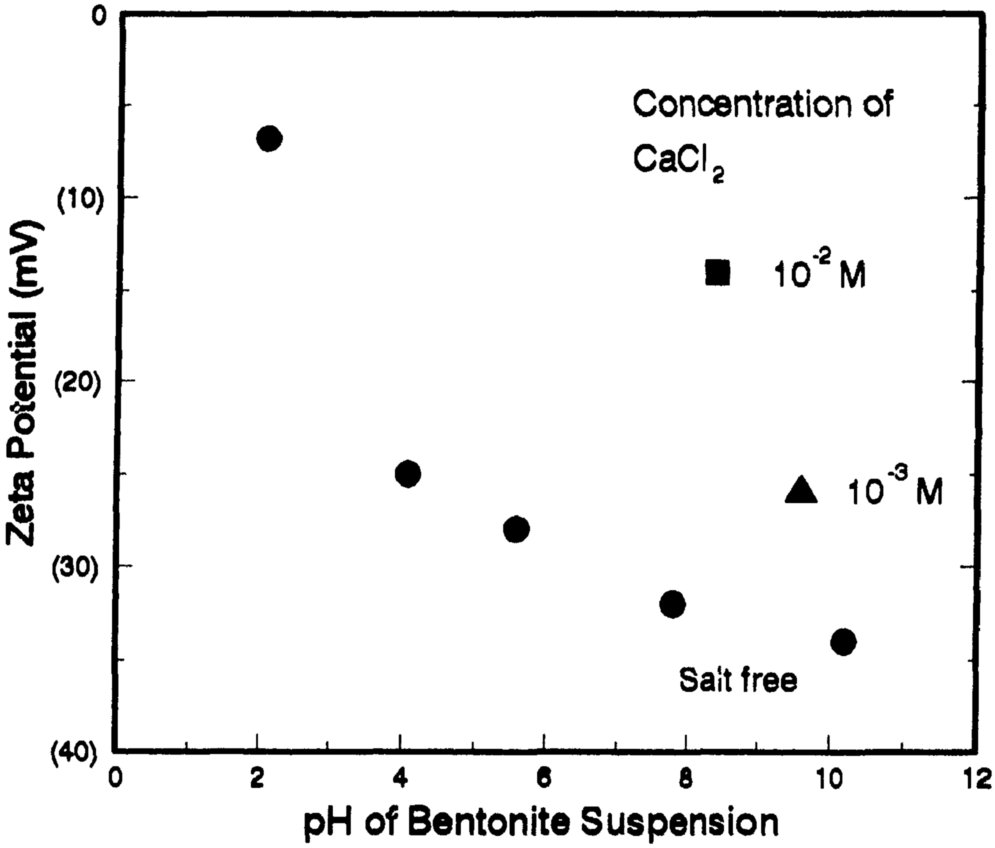


Figure 2-3 Zeta potential of Bentonite as a function of pH (Ju, 1990)

2.4 Experimental Procedure

A suspension was prepared from a weighed amount of oven-dried material and a weighed amount of $CaCl_2$ solution prepared from reagent grade $CaCl_2$ and distilled water. Dry material was weighed in a beaker and the necessary amount of solution was weighed in a second beaker. The material was added to the water gradually while mixing using a magnetic stirrer. The total weight of the beaker containing the liquid and solid was recorded after homogenizing for 15 minutes. A fresh filter sheet was wetted with methanol and fixed in place. If the sheets were not wetted, water flow was retarded at the beginning of a run.

The suspension was then poured slowly into the cylinder to the desired height The beaker containing the remaining suspension was weighed and the weight of the suspension in the bed was determined by difference. The upper electrode was fixed so that it contacted the top of the bed. In the experiments with rotation of upper electrode the motor was fixed on the top of the shaft. The apparatus was left for enough time after setting it up to make sure there was no water removal due to the compression or settling. At low $CaCl_2$ concentration no gravity drainage of water occurred and electroosmotic dewatering began immediately

For the first 10 minutes after the voltage or current was applied, the volume of water removed by electroosmosis was recorded every minute, then every five minutes and near the end of dewatering, every ten minutes. With a constant applied voltage the current was recorded every ten minutes. Voltage differences were recorded every ten minutes in constant current experiments The output voltage from the shunt in the circuit in the interrupted dewatering runs was recorded from the screen of a storage Oscilloscope four to six times during dewatering.

At the end of dewatering the cake was sectioned for moisture determination. The dewatered cake was carefully pushed out of the disassembled cylinder and cut perpendicular to its axis into three disks of approximately equal thickness. Each disk was weighed as soon as it was cut and then it was dried at $105°C$ to a constant weight. The mass of water in each piece was calculated by difference. Occasionally the pH of the collected water from Bentonite suspensions was measured. In all cases the pH of the water removed was above 12, as Ju reported (Ju, 1990).

2.5 Treatment of Data

A parameter used subsequently is the total energy consumed, denoted, E_T . It was computed from the current, voltage and time by:

$$E_T = \int_0^t i\, V\, dt \qquad (2\text{-}2)$$

where i = current (A)

V = voltage (V)

t = time (s)

The integral was computed by Simpson's rule.

Two important parameters related to the effectiveness of electroosmotic dewatering are:

1) the water flux per unit charge

and

2) the energy of dewatering

Both parameters require the rate of water removal, $\dot{Q}$. This rate represents the time variation derivative of the volume of water collected, Q:

$$\dot{Q} = \frac{dQ}{dt} \tag{2-3}$$

The volume versus time data were fitted to a second order polynomial by least squares and the derivative was calculated analytically. The polynomial was fitted to all but the last two or three data points.

The water flux per unit charge, denoted W, was computed from

$$W = 9.65\times10^4 \, (\dot{Q}\, \rho \,/\, M\, i) \tag{2-4}$$

where ρ is the density of water, M is the molecular weight of water (18.0 g/mole) and one Faraday of charge is 9.65×10^4 Coulombs. The units of W are moles of water per Faraday.

The energy of dewatering, denoted e_d , is defined as

$$e_d = \frac{electrical\ \ power}{rate\ \ of\ \ water\ \ removal} \tag{2-5}$$

Hence,

$$e_d = \frac{i\, V_0}{\dot{Q}\, \rho \,/\, M} \tag{2-6}$$

where V_0 is the overall voltage. The units of e_d are joules per mole

CHAPTER 3

DIRECT CURRENT ELECTROOSMOTIC DEWATERING

The electroosmotic dewatering of Bentonite suspensions under constant applied direct current and voltage (DC) was studied experimentally in the apparatus described in Chapter 2. A few runs with kaolin and red clay were also carried out for comparison.

3.1 General Features of Dewatering under Constant Current

The volume of water removed and the overall voltage drop across the bed for three replicates of a typical experiment are plotted in Figs. 3-1 and 3-2 for 90 mA current, 2.0 cm initial bed height, 9.1 wt % initial solid content and no electrolyte. Figure 3-1 shows that the volume of water removed increased approximately linearly for the first 40 minutes and then increased more slowly. The overall voltage drop decreased initially, reached a minimum and then increased (see Fig. 3-2).

Replicate data for water removed in Fig. 3-1 show good agreement, with the maximum deviation of the data from the average value of approximately ±2.5% . The maximum deviation of the data for voltage drop was approximately ±5% from the average value. There is more scatter in the voltage data because generation of gas at the upper electrode alters the degree of electrical contact between the bed and the electrode.

Data from the replicate runs are presented in different formats in Figs. 3-3 and 3-4 (see Chapter 2 for a description of the method of calculation of the

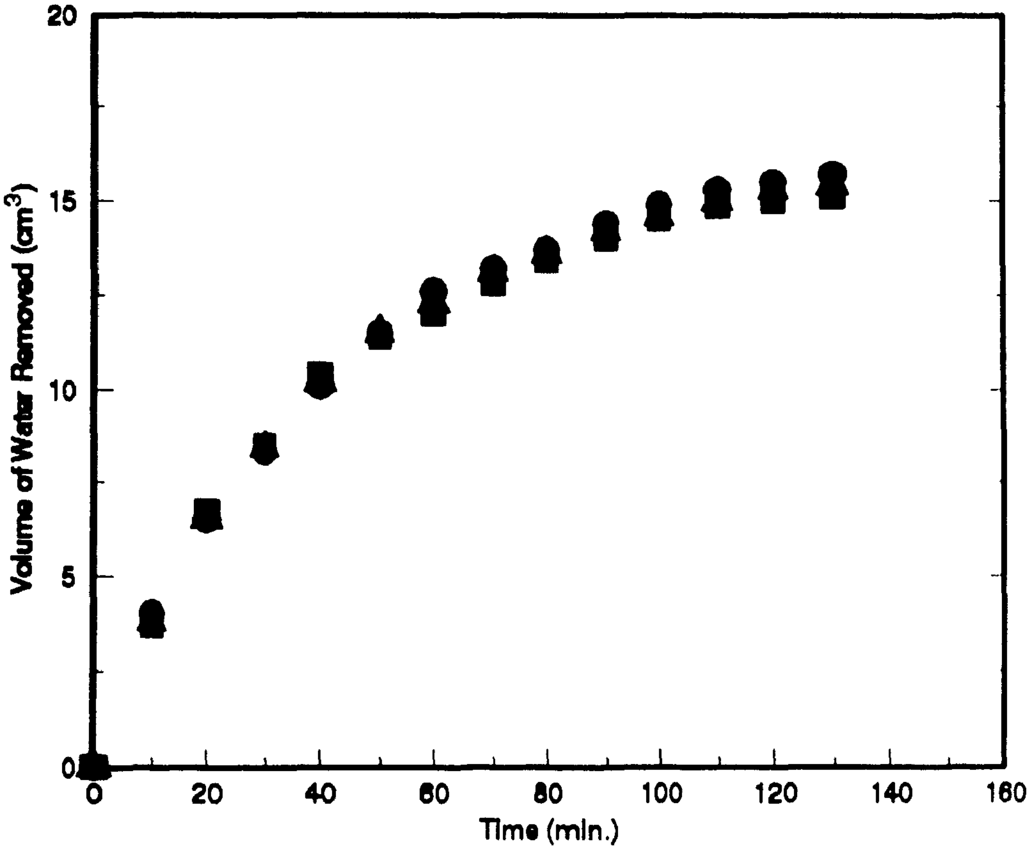


Figure 3-1 Volume of water removed vs. time for Bentonite under constant DC current. Data from three replicate runs. (9.1 wt%; 0 M; 2.0 cm; 90 mA)

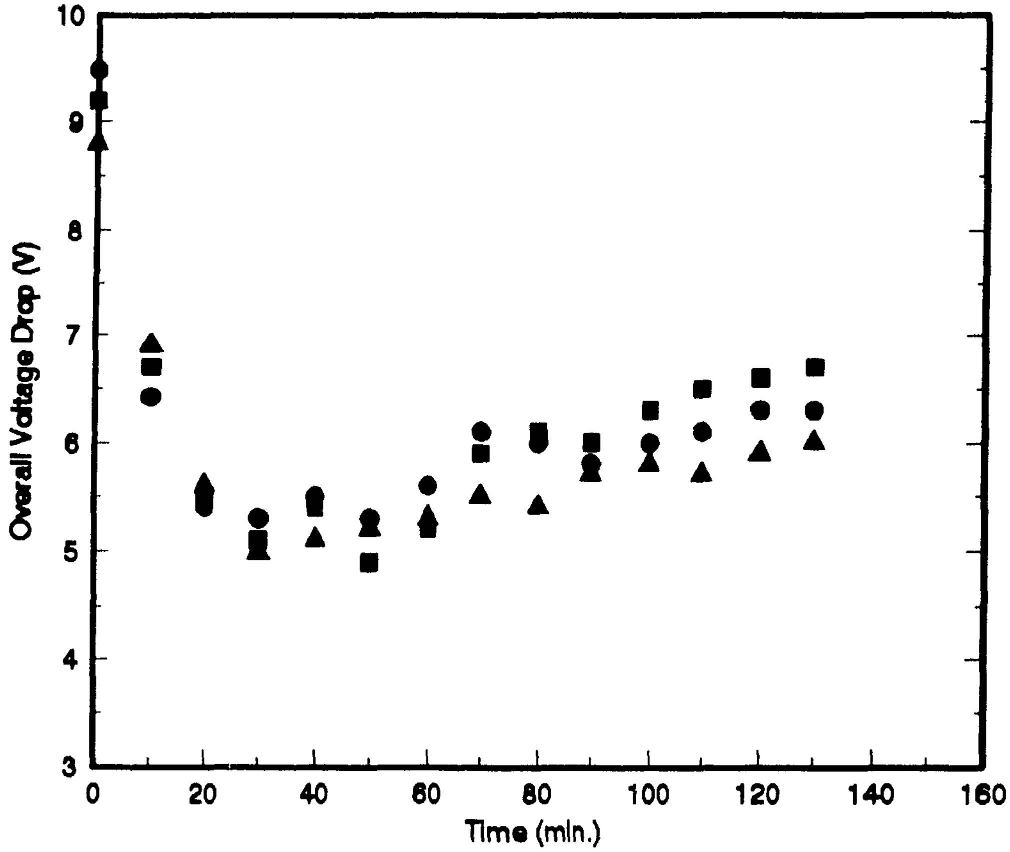


Figure 3-2 Variation of overall voltage with time for Bentonite under constant DC current. Data from three replicate runs. (9.1 wt%; 0 M; 2.0 cm; 90 mA)

parameters from the recorded data). The water flux per unit charge is plotted against the percent water removed in Fig. 3-3. The energy required to remove a mole of water by electroosmosis is plotted in Fig. 3-4 against the percent water removed. Since the calculations for both figures involved differentiation of the data in Fig. 3-1, the deviation of data from the average value was about ±14% for Fig 3-3 and ±12% for Fig. 3-4 except above 30% water removed where the scatter was larger.

The general characteristics of dewatering under constant current are shown in Figs. 3-1 through 3-4. The volume of water removed increased nearly linearly over the first 40 minutes while the overall voltage drop decreased over the same period. Beyond 40 minutes the rate of water removal decreased while the voltage across the bed increased. The minimum in the voltage reflects opposing trends. The electric resistance of the bed decreases as the height of the bed decreases when water is removed. But it increases under the influence of the unsaturated layer formed in the dewatered bed and because of gas produced by electrolysis (Yoshida, 1985).

The dewatering process may be considered to occur in two stages. In the first stage, where in 40 minutes approximately 20% of the water was removed, the moles of water transported per Faraday decreased about 25% and the energy of dewatering was low, (e.g. about 5% of the heat of vaporization). Beyond 20% removal, the water transported per Faraday decreased rapidly while the energy of dewatering increased rapidly.

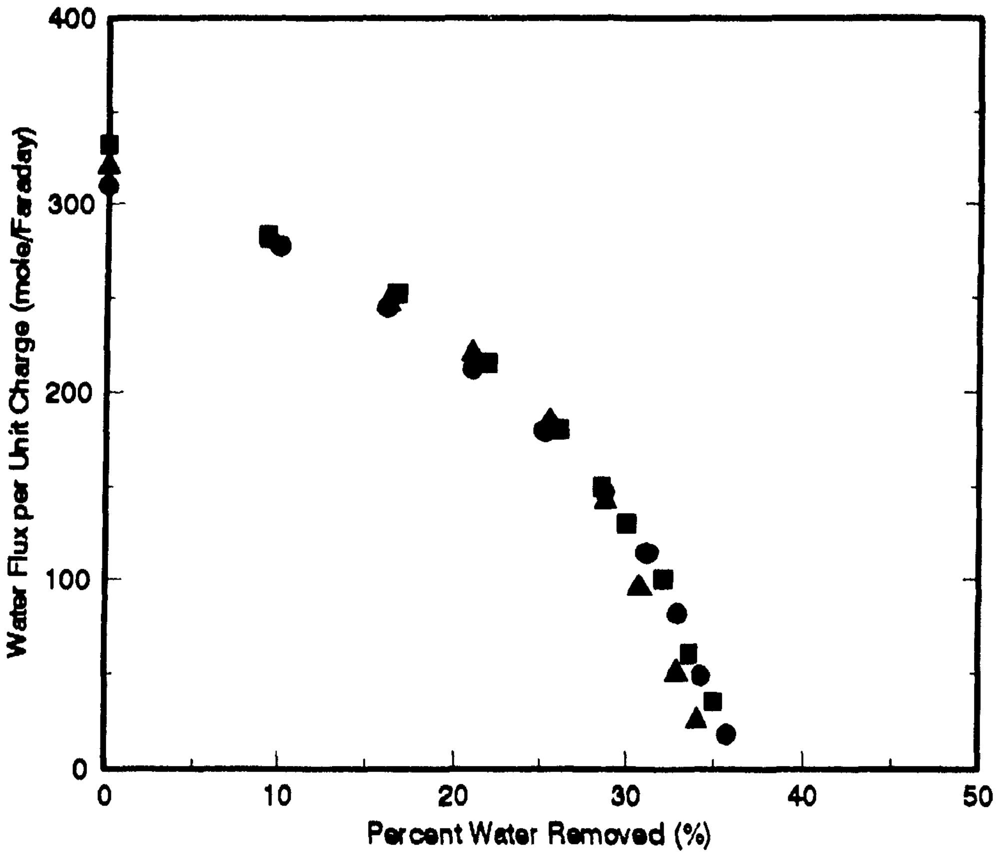


Figure 3-3 Water flux per unit charge vs. percent water removed for Bentonite under constant DC current. Data from three replicate runs. (9.1 wt%; 0 M; 2.0 cm; 90 mA)

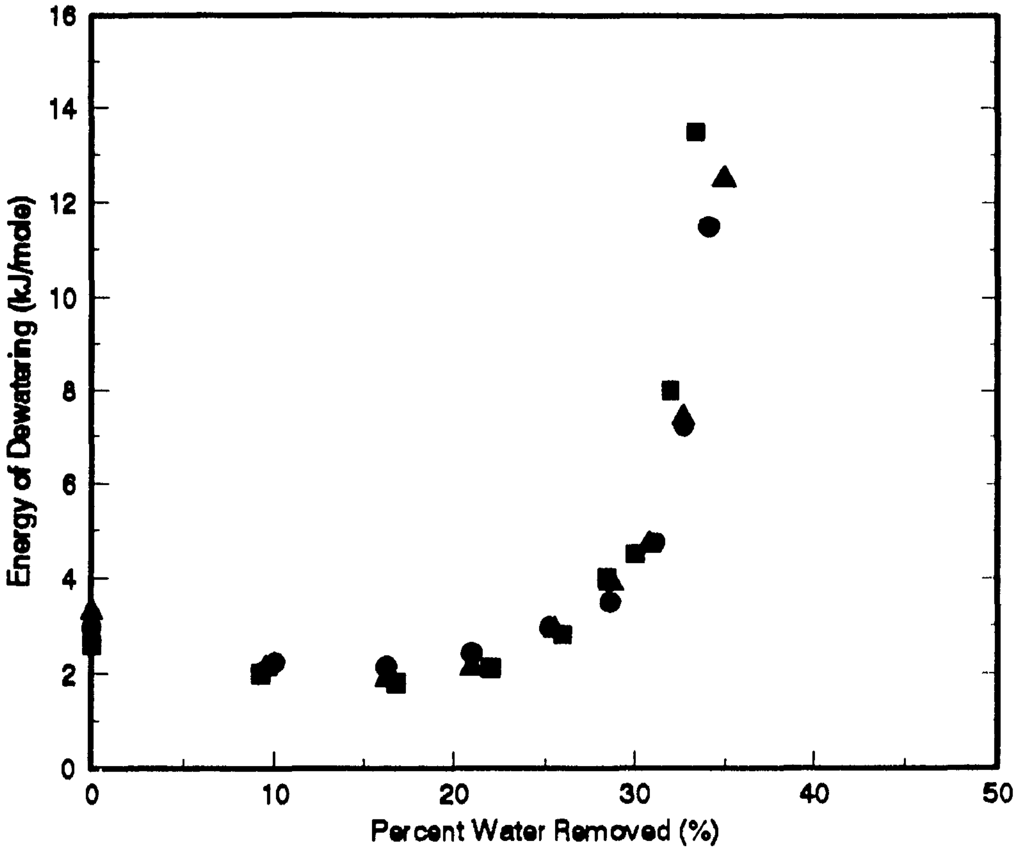


Figure 3-4 Energy of dewatering vs. percent water removed for Bentonite under constant DC current. Data from three replicate runs. (9.1 wt%; 0 M; 2.0 cm; 90 mA)

3.2 General Features of Dewatering under Constant Voltage

Three replicates of a typical experiment are presented in Figs. 3-5 and 3-6. Figure 3-5 shows that water was removed up to 140 minutes. The current went through a maximum at about 40 minutes and then decreased to a constant value (see Fig. 3-6). Replicate data for water removed, Fig. 3-5, and current, Fig. 3-6, show good agreement. For water removed the maximum deviation of data from the average value was approximately ±4% , while for the current it was approximately ±6% . Data from the replicate runs are also presented in Figs. 3-7 and 3-8 in the formats identical to those shown in Figs. 3-3 and 3-4. The maximum deviation of the data from the average value was about ±17% for Fig. 3-7 and ±20% for Fig. 3-8 except above 30% water removed.

The general characteristics of dewatering under constant voltage are shown in Figs. 3-5 through 3-8. The rate of water removal was initially constant and then decreased with time as the bed dewatered; see Fig. 3-5. The current increased up to 40 minutes of dewatering and then decreased. The electrical resistance of the bed increases as the percentage of solids, which are non conducting, increases but it decreases as the height decreases The maximum in the current reflects these two opposing trends If the applied voltage is low, there is no maximum current (Yoshida et al., 1985 and Ju, 1990). In addition, good electrical contact between the bed and the upper electrode may be hampered by the gas evolved at the upper electrode. As water was removed, the volume of the bed and the sizes of the pores decreased making water more difficult to remove as shown in Figs. 3-7 and 3-8.

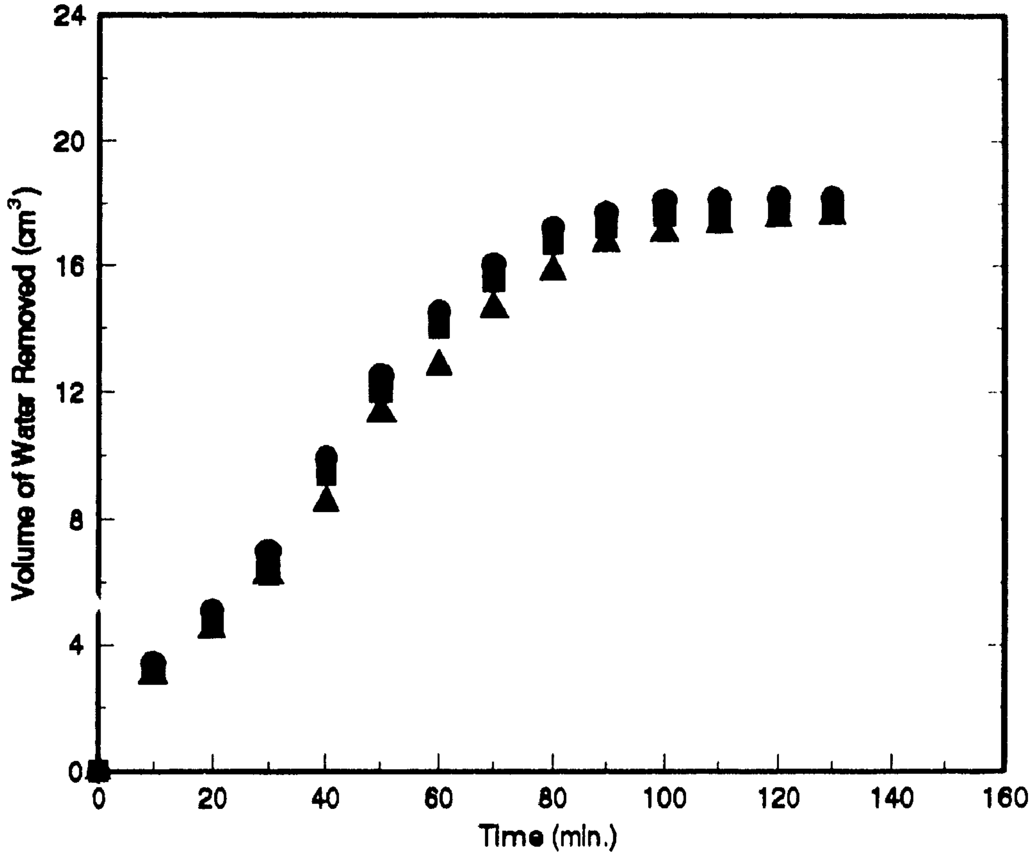


Figure 3-5 Volume of water removed vs. time for Bentonite under constant DC voltage. Data from three replicate runs. (9.1 wt%; 0 M; 2.0 cm; 5.5 V)

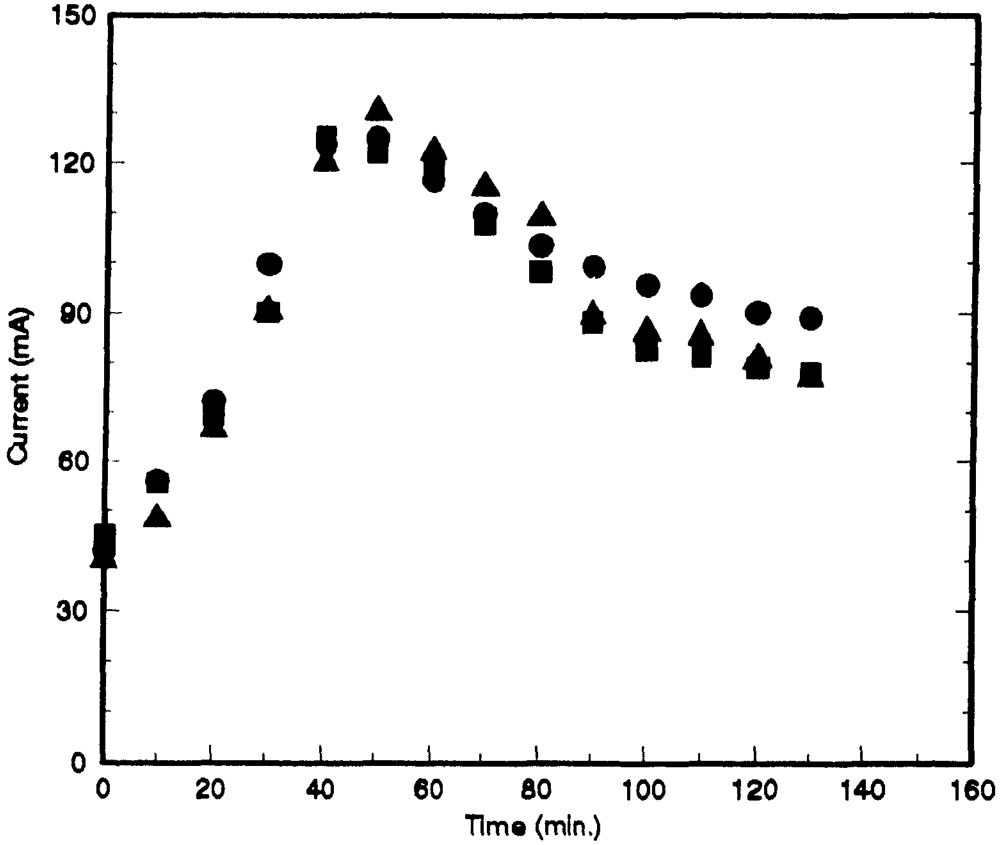


Figure 3-6 Variation of current with time for Bentonite under constant DC voltage. Data from three replicate runs. (9.1 wt%; 0 M; 2.0 cm; 5.5 V)

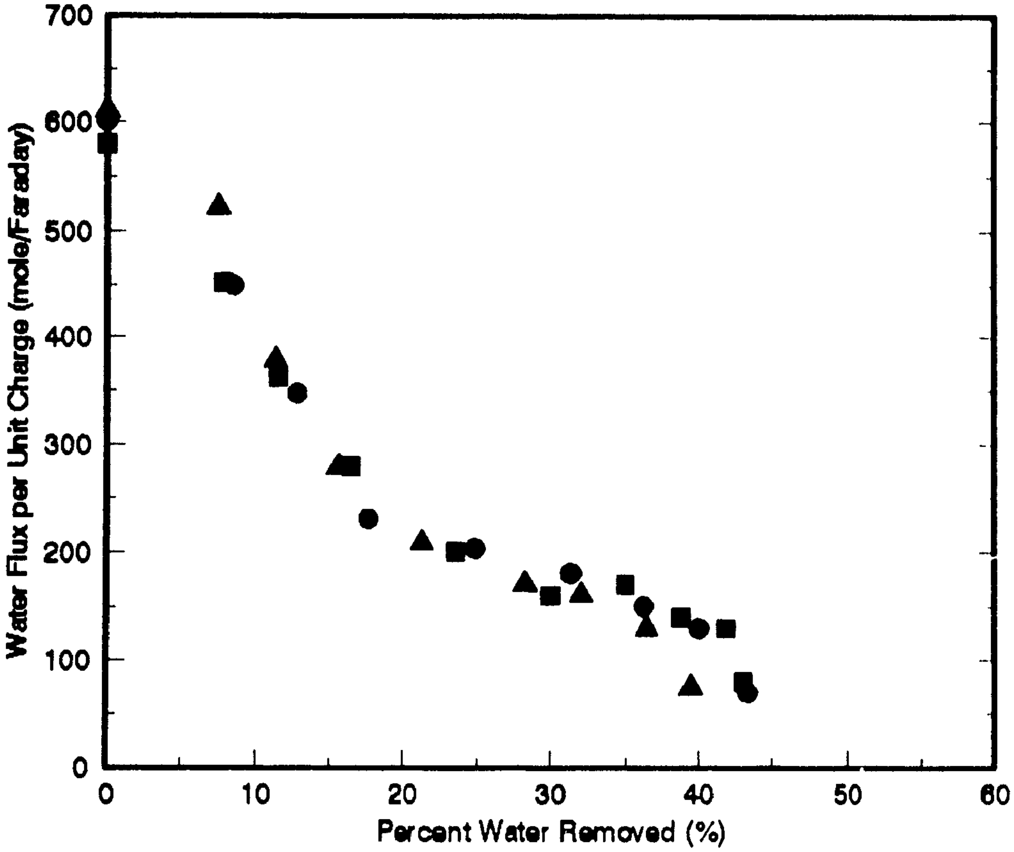


Figure 3-7 Water flux per unit charge vs. percent water removed for Bentonite under constant DC voltage. Data from three replicate runs. (9.1 wt%; 0 M; 2.0 cm; 5.5 V)

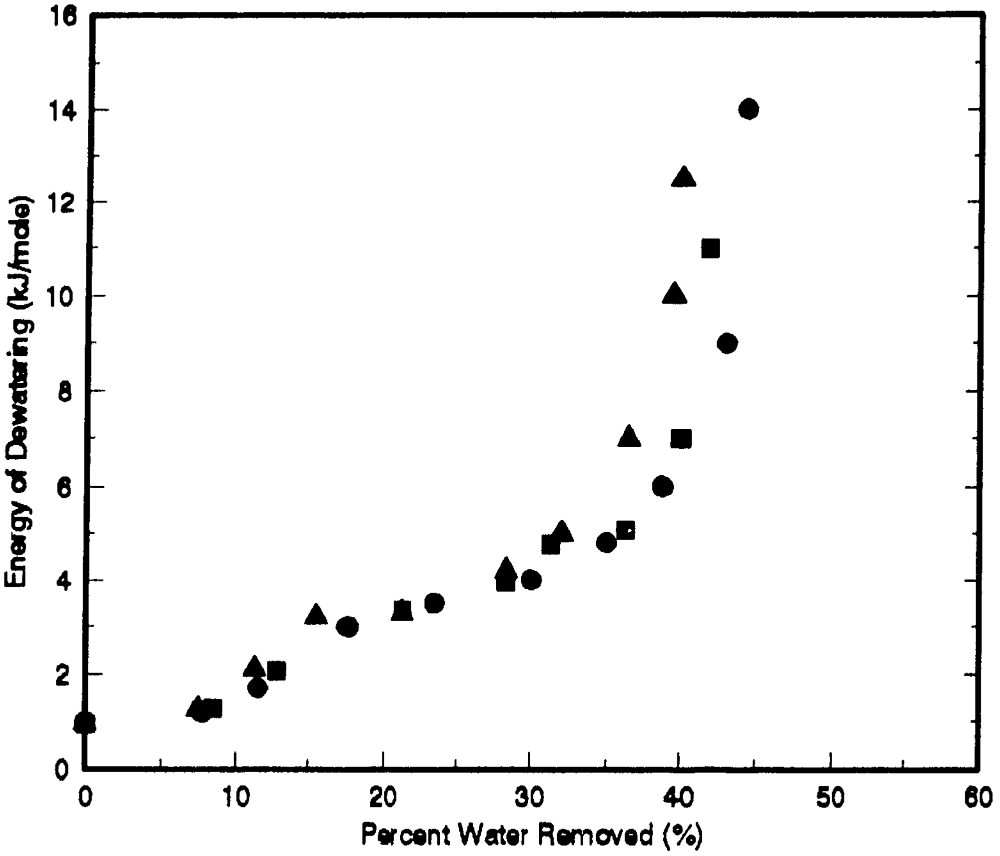


Figure 3-8 Energy of dewatering vs. percent water removed for Bentonite under constant DC voltage. Data from three replicate runs. (9.1 wt%; 0 M; 2.0 cm; 5.5 V)

3.3 Effect of Initial Bed Height

Figures 3-9 through 3-12 show the effect of the initial bed height on the electroosmotic dewatering (abbreviated as EOD) rate. All data are for an initial suspension of 9.1 wt% Bentonite and a current of 90 mA. Distilled water was used to prepare the suspensions.

Figure 3-9 shows the volume of water removed as a function of time for various initial bed heights. Since 2.0 cm initial bed height contained the largest amount of water, the final amount of water removed was highest for the 2.0 cm bed, 15.7 cm^3, and lowest for the 0.5 cm bed, 4.5 cm^3. The variation of the overall voltage drop with time for the three initial bed heights is shown in Fig. 3-10. For all three heights, the overall voltage drop decreased in the first period of nearly linearly increasing volume of water removed. At heights of 2.0 cm and 1.0 cm, large cracks appeared in the cake after about 30 minutes of EOD. This led to large and erratic changes in the overall voltage drop as illustrated by the scatter in the data shown in Fig. 3-10.

Figure 3-11 shows the variation of the water flux per unit charge with water removal for three bed heights. The initial water flux per unit charge was larger for larger bed heights. After 15 minutes a bed of 1.0 cm initial height had a larger water flux per unit charge than the others. Figure 3-12 shows the energy of dewatering for the three initial bed heights. The energy expenditure to remove 30% water was approximately the same for all runs. Also it was less than 10% of heat of vaporization of water, which is 43.8 kJ/mol. Since more water was removed for the 1.0 cm bed and less for the 2.0 cm bed, the energy expenditure increased dramatically at about 42% removal, (14.7% average solid content) for 1.0 cm and

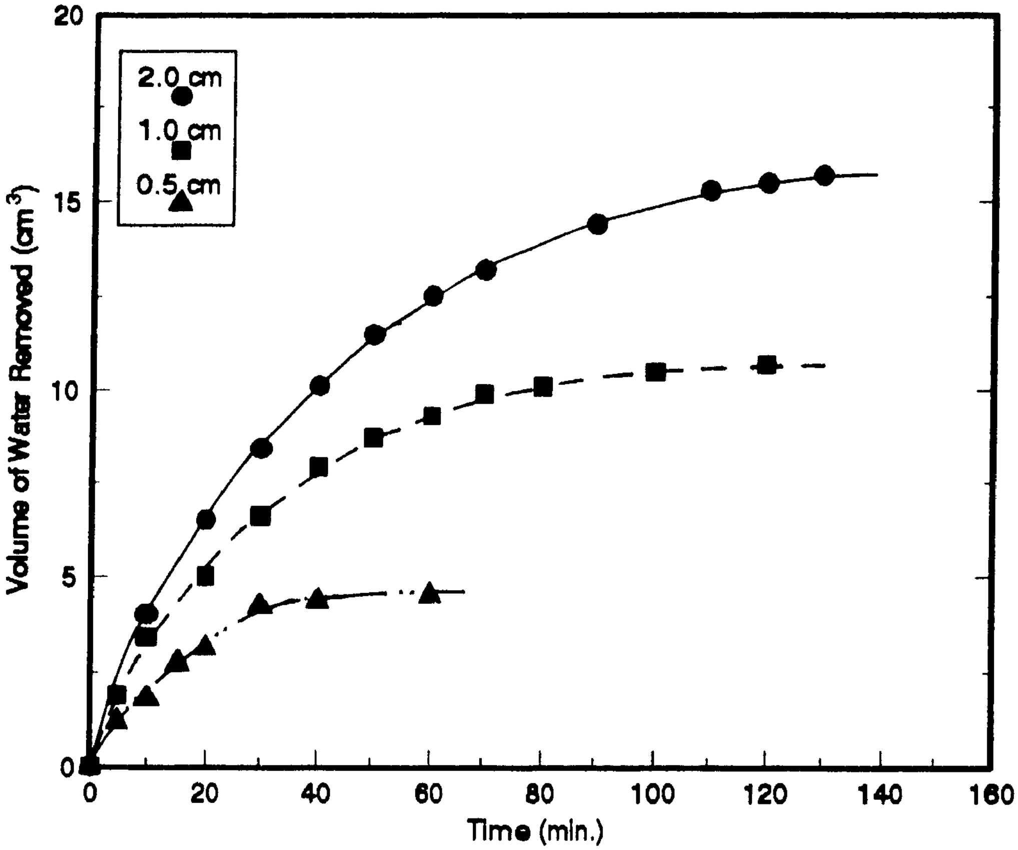


Figure 3-9 Volume of water removed vs. time for Bentonite under constant DC current. (9.1 wt%; 0 M; 90 mA)

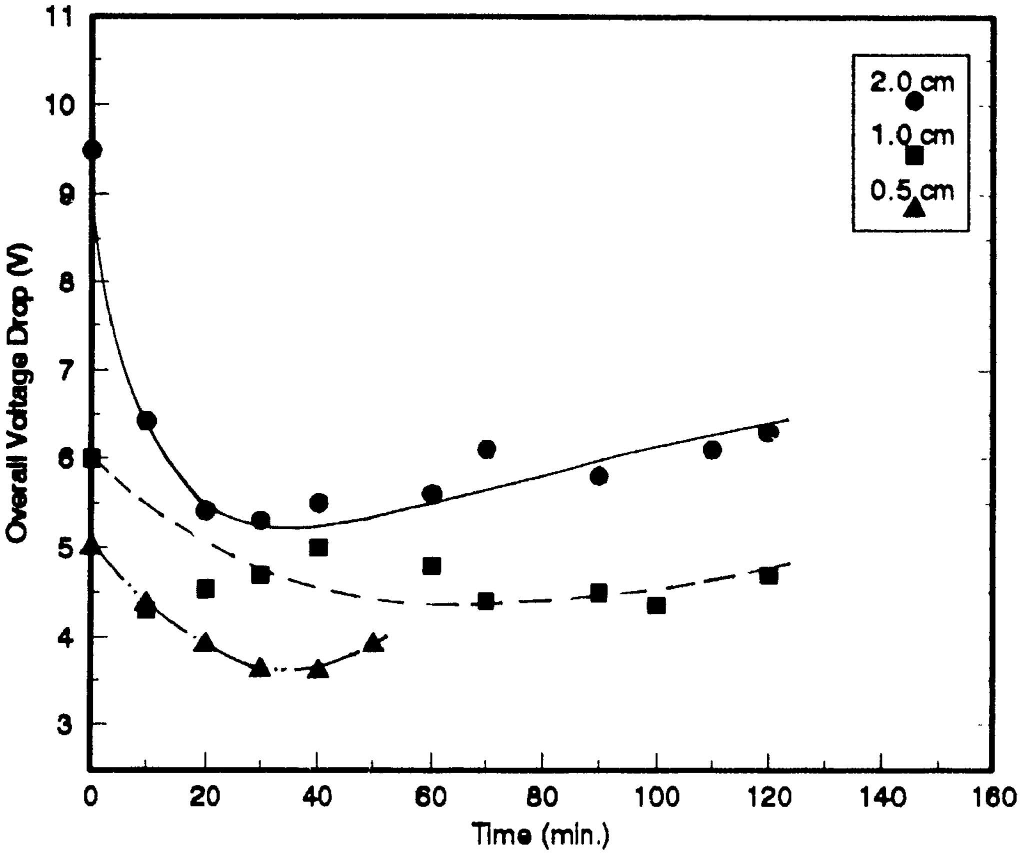


Figure 3-10 Variation of overall voltage with time for Bentonite under constant DC current. (9.1 wt%; 0 M; 90 mA)

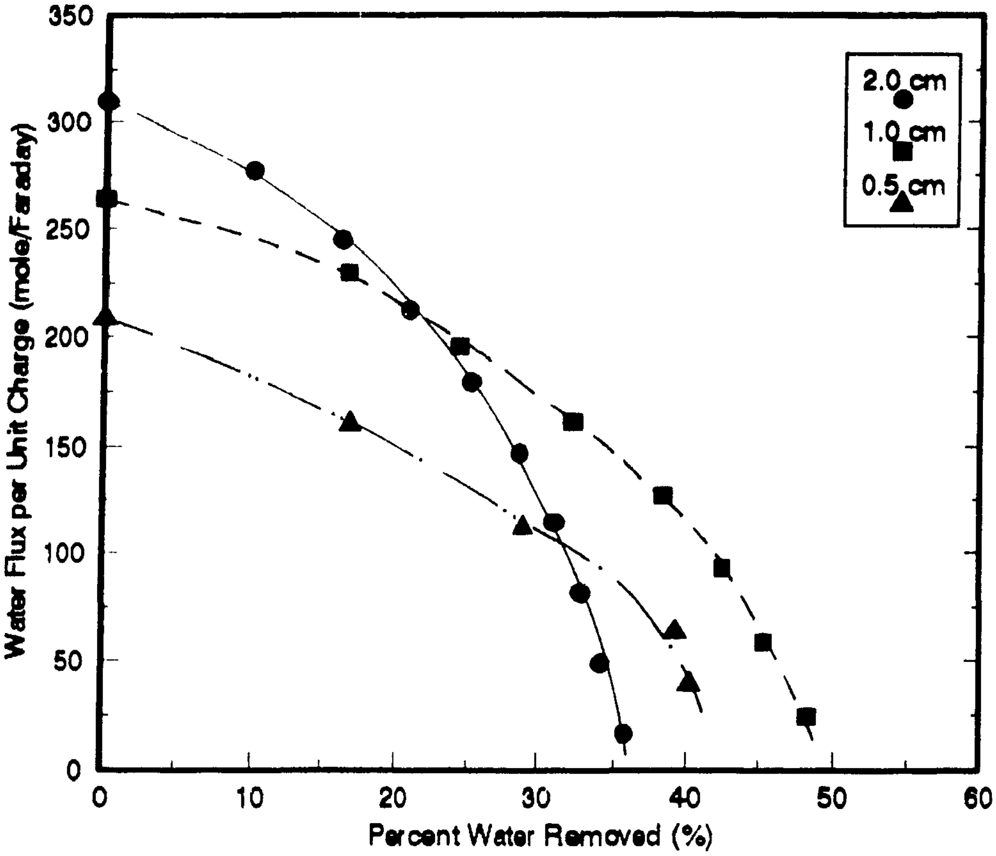


Figure 3-11 Water flux per unit charge vs. percent water removed for Bentonite under constant DC current. (9.1 wt%; 0 M; 90 mA)

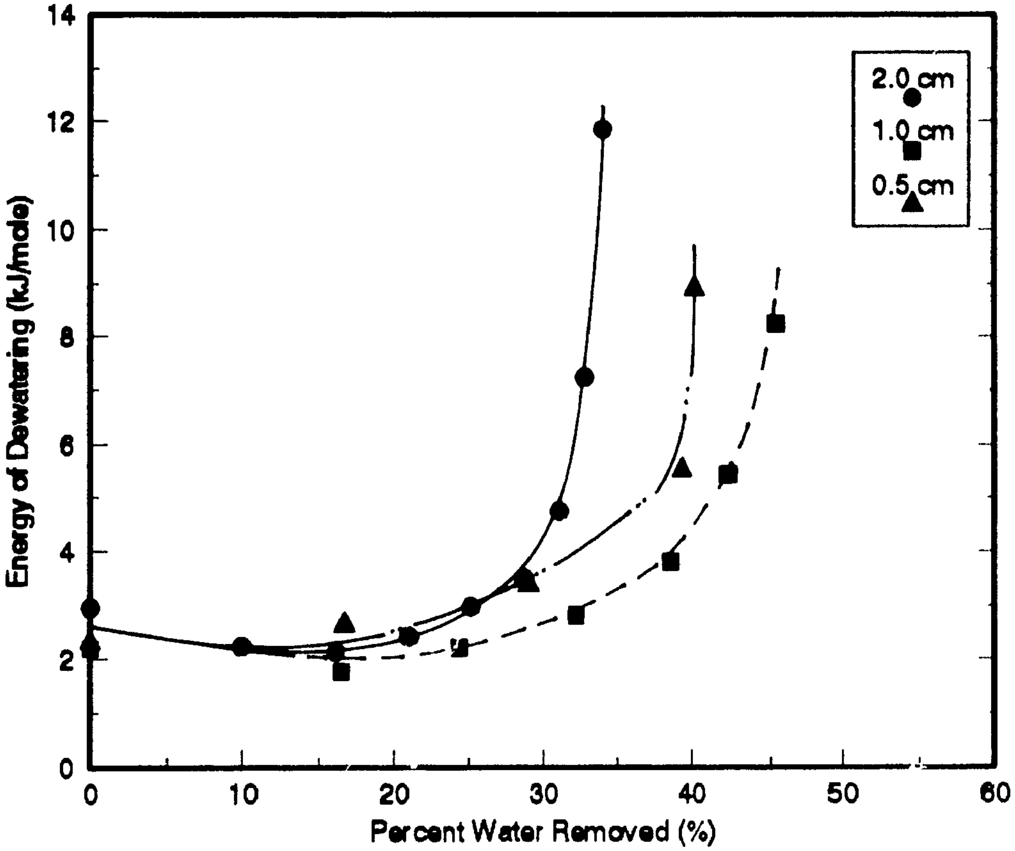


Figure 3-12 Energy of dewatering vs. percent water removed for Bentonite under constant DC current. (9.1 wt%; 0 M; 90 mA)

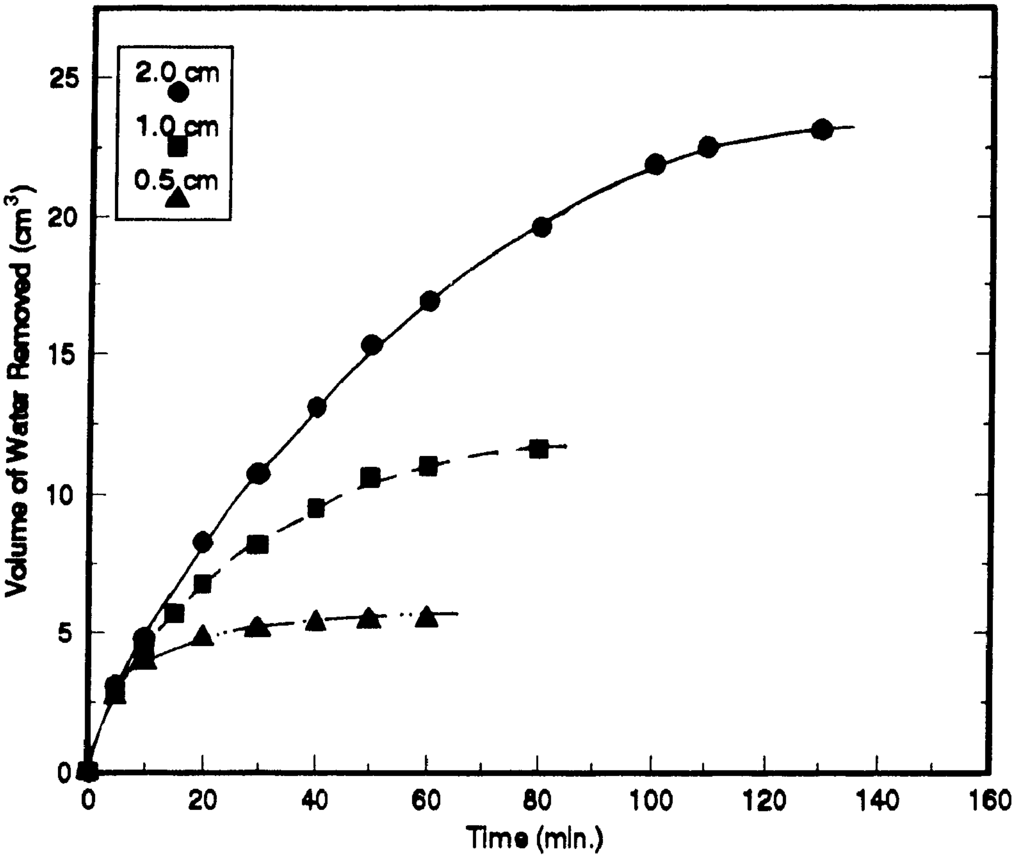


Figure 3-13 Volume of water removed vs. time for Bentonite under constant DC current. (9.1 wt%; 0.01 M; 90 mA)

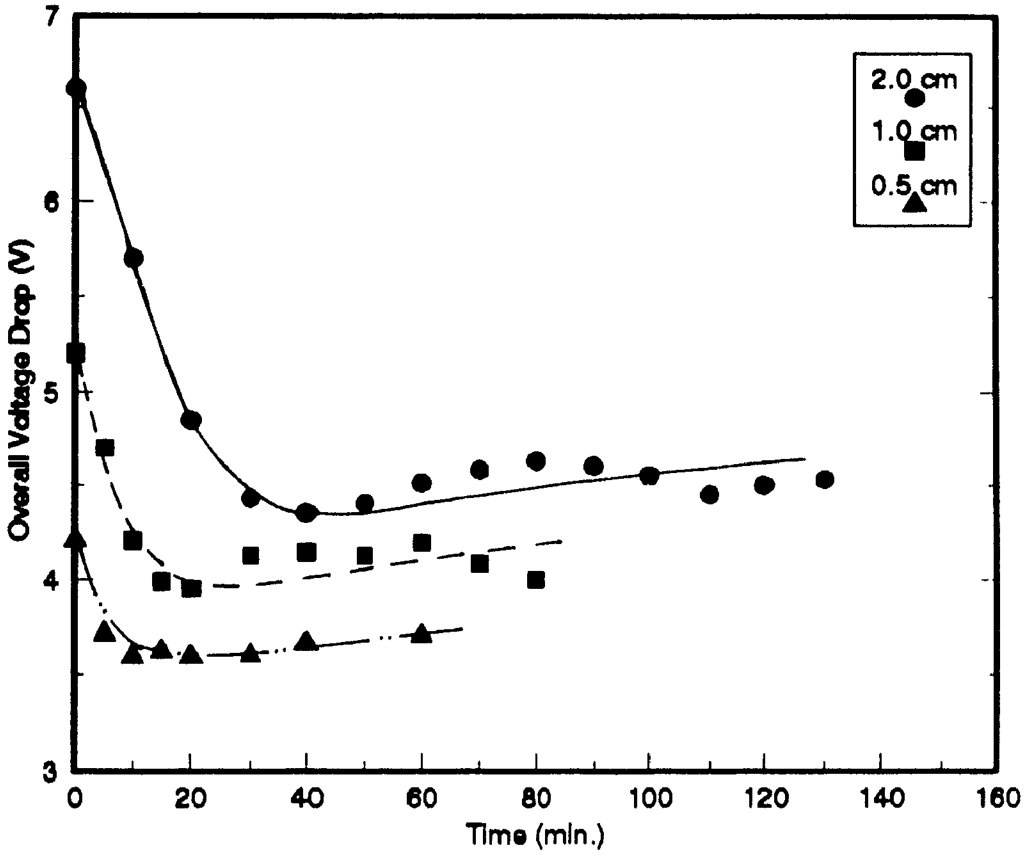


Figure 3-14 Variation of overall voltage with time for Bentonite under constant DC current. (9.1 wt%; 0.01 M; 90 mA)

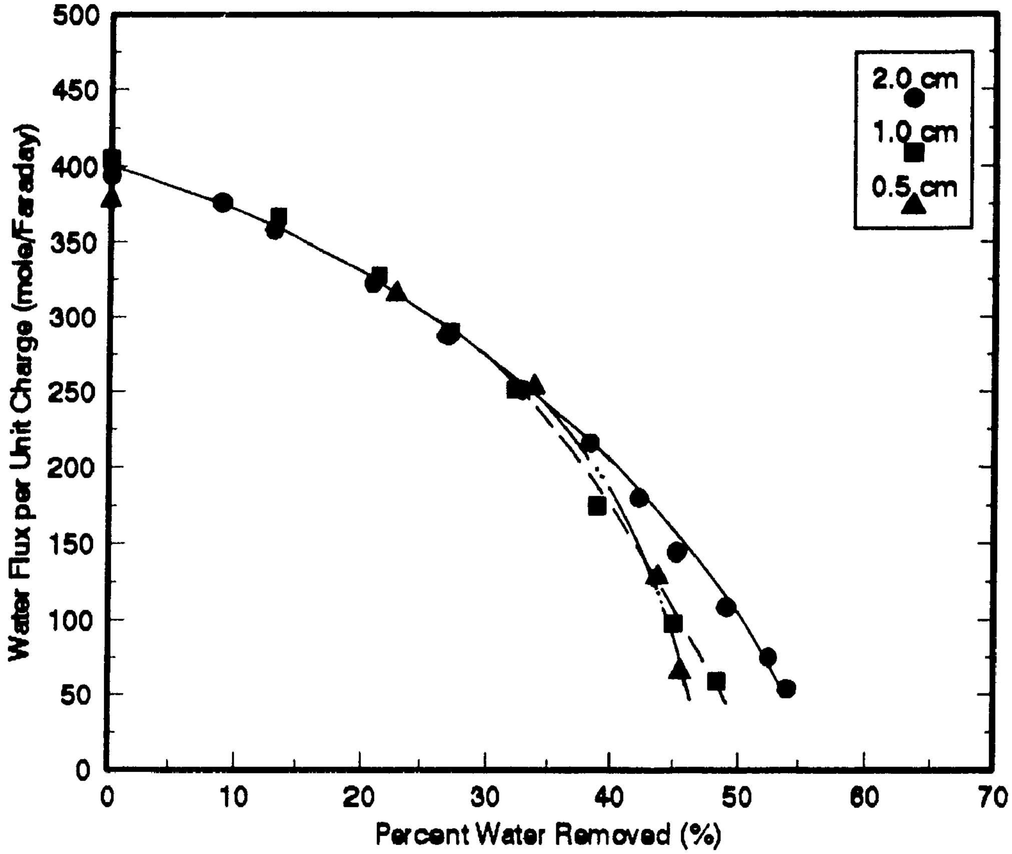


Figure 3-15 Water flux per unit charge vs. percent water removed for Bentonite under constant DC current. (9.1 wt%; 0.01 M; 90 mA)

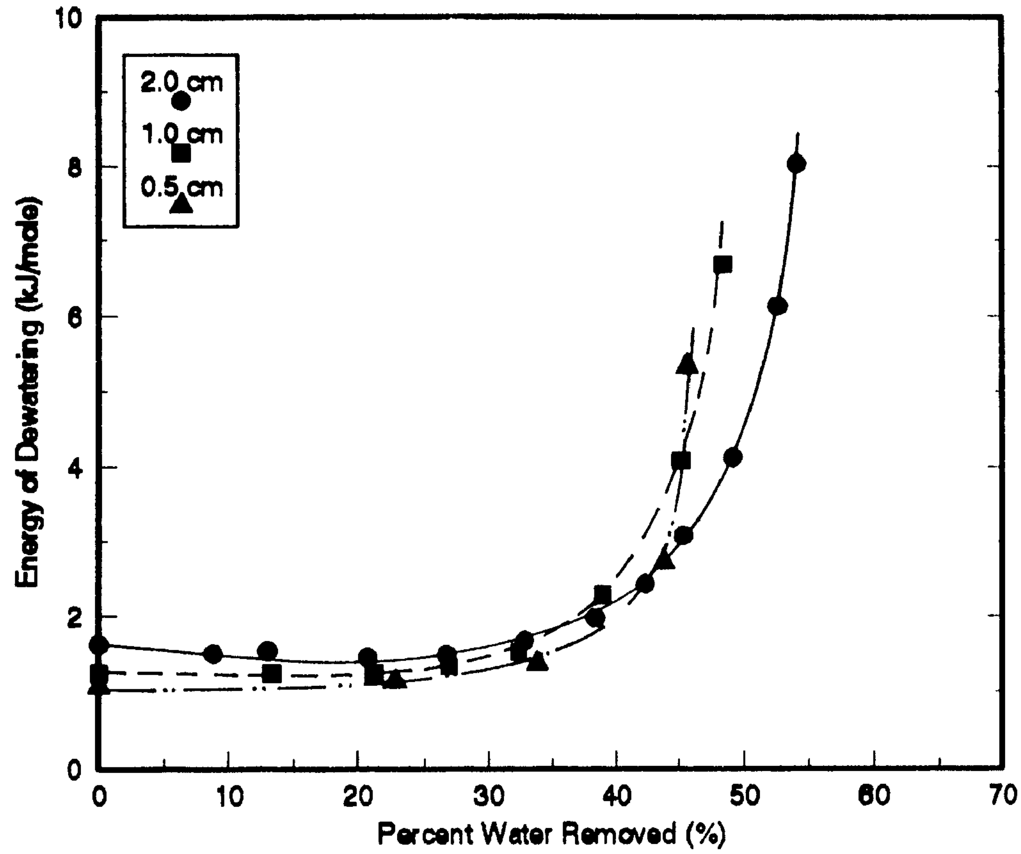


Figure 3-16 Energy of dewatering vs. percent water removed for Bentonite under constant DC current. (9.1 wt%; 0.01 M; 90 mA)

about 31% removal, (12.5% average solid content) for 2.0 cm initial bed height.

Figures 3-13 through 3-16 show the effect of the initial bed height on the dewatering rate for the same conditions except that 10^{-2} M $CaCl_2$ was used to prepare the initial suspension. Figure 3-13 shows the volume of water removed as a function of time. The final amount of water removed was larger at the higher bed height; 23.2, 11.7 and 5.6 cm^3 of water removed for initial heights of 2.0, 1.0 and 0.5 cm, respectively. In Fig. 3-14 the overall voltage drop data are plotted against time. The scatter in the overall voltage drop is much smaller than in Fig. 3-10 where no electrolyte was used. Figures 3-15 and 3-16 show that the water flux per unit charge and the energy consumption for dewatering as functions of the water removal are essentially independent of the initial bed height.

3.4 Effect of Rotation of the upper Electrode

Figures 3-17 through 3-20 show the effect of rotation of the upper electrode at 0, 40 and 70 rpm. In Figs. 3-17 and 3-18 all data are for an initial solid content of 9.1 wt% Bentonite in 10^{-3} M $CaCl_2$, an initial height of 1.0 cm and a current of 50 mA. Figures 3-17 and 3-18 display the time variation of the volume of water removed and the overall voltage drop, respectively. There was no effect of rotation. The final percent water removed was essentially the same for all three cases; 44, 42 and 43% for 0, 40 and 70 rpm, respectively.

Figures 3-19 and 3-20 show similar results for an initial suspension of 9.1 wt% Bentonite in 10^{-2} M $CaCl_2$, an initial height of 1.5 cm and a current of 30 mA. These figures again show that there is no effect of rotation.

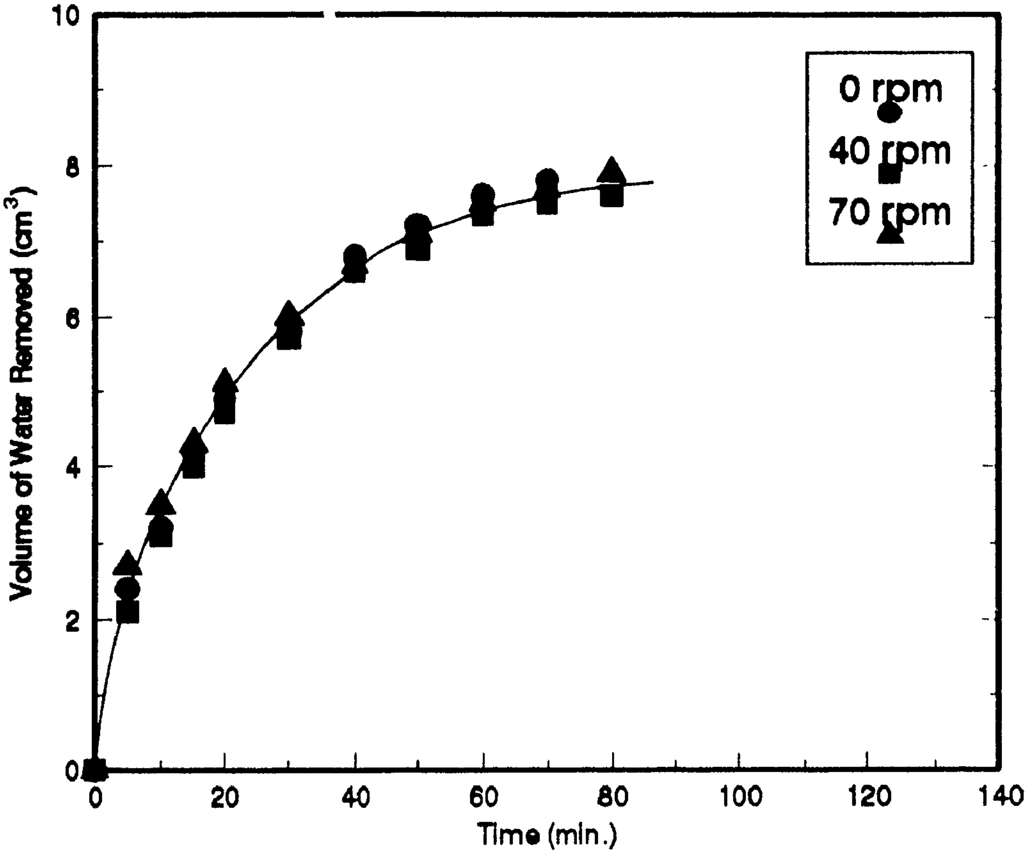


Figure 3-17 Volume of water removed vs. time for Bentonite under constant DC current. (9.1 wt%; 0.001 M; 1.0 cm; 50 mA)

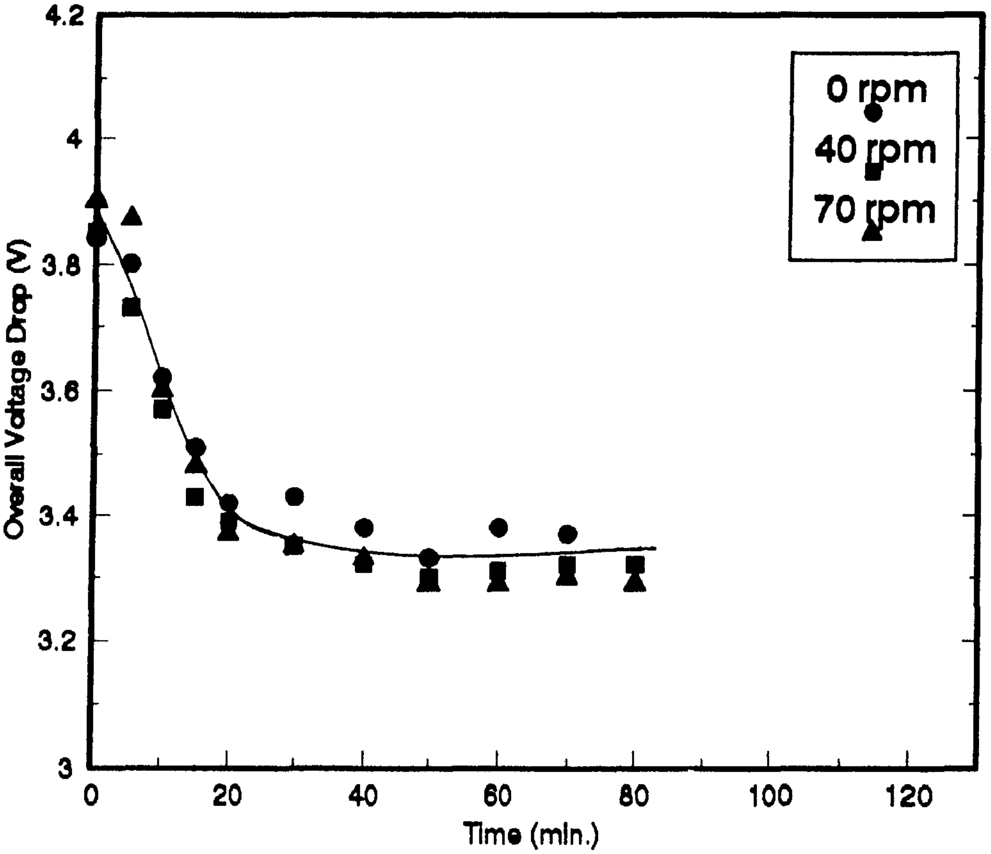


Figure 3-18 Variation of overall voltage with time for Bentonite under constant DC current. (9.1 wt%; 0.001 M; 1.0 cm; 50 mA)

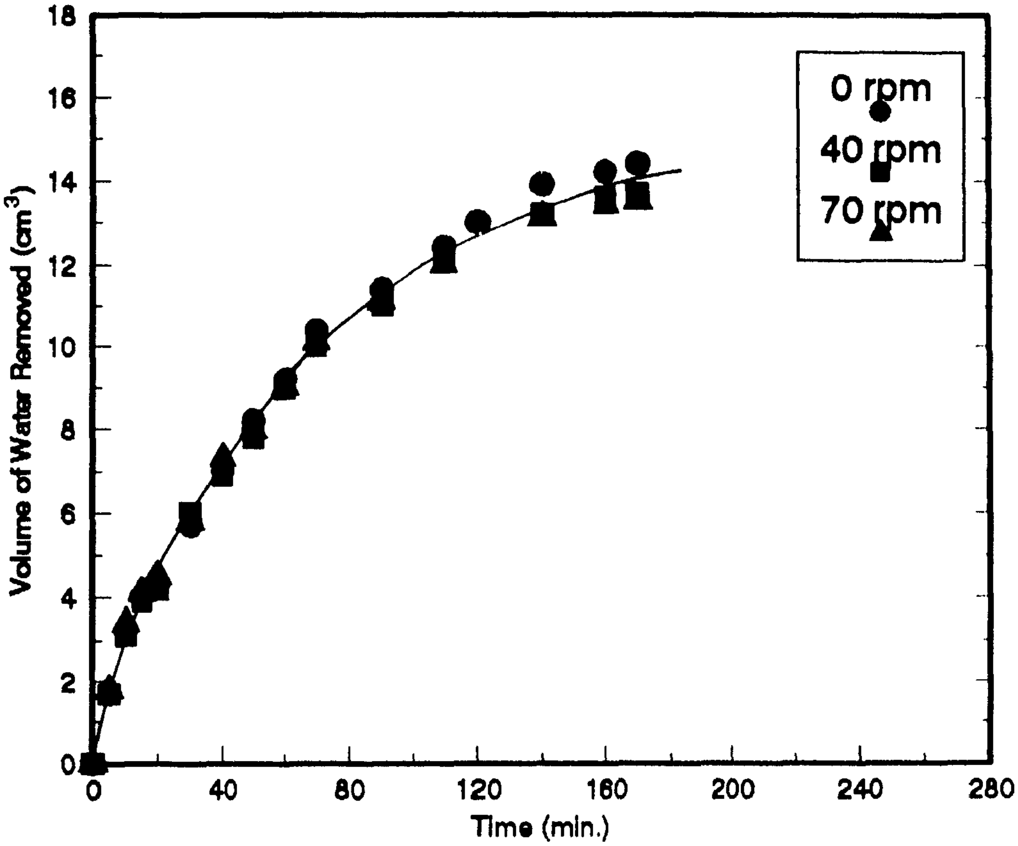


Figure 3-19 Volume of water removed vs. time for Bentonite under constant DC current. (9.1 wt%; 0.01 M; 1.5 cm; 30 mA)

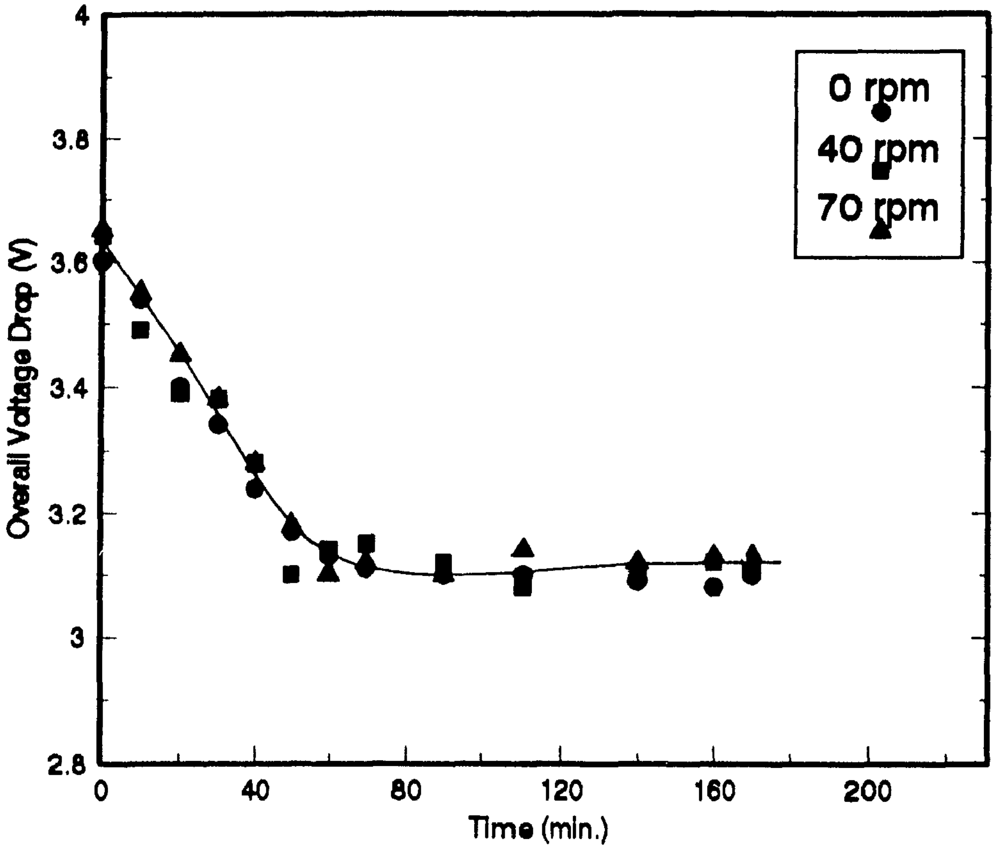
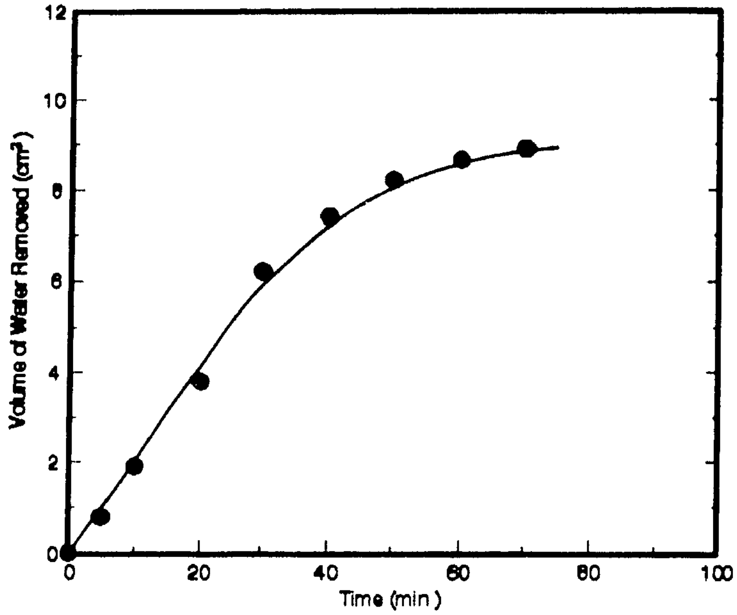


Figure 3-20 Variation of overall voltage with time for Bentonite under constant DC current. (9.1 wt%; 0.01 M; 1.5 cm; 30 mA)

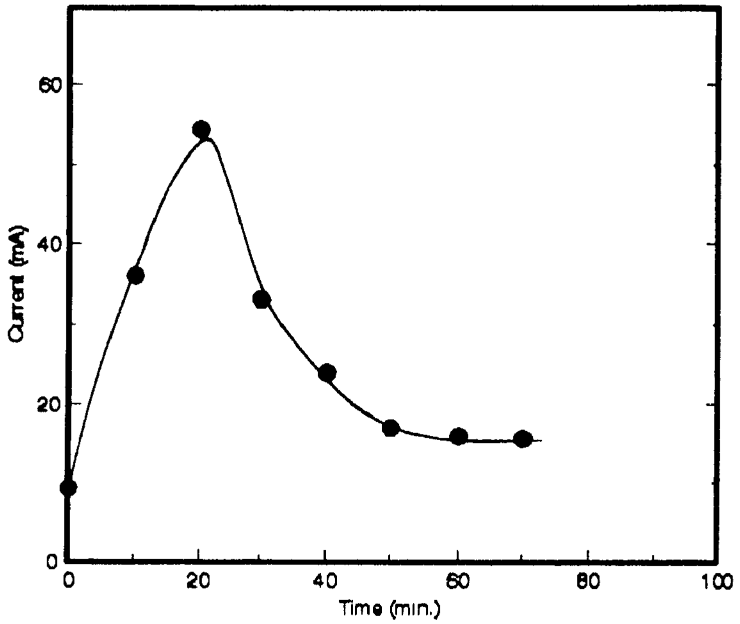
3.5 Electroosmotic Dewatering of Kaolin and Red Clay under Constant Voltage

The volume of water removed and the current for electroosmotic dewatering of kaolin with an applied voltage of 5.5 V are presented in Fig. 3-21. The initial solid content was 25 wt% in distilled water with an initial bed height of 1.0 cm. After 70 minutes about 62% of initial water was removed, see Fig. 3-21a, and the average solid concentration was 46 wt%. Figure 3-21b shows that the current exhibited a sharp maximum.

Figure 3-22 shows similar data for red clay with 45 wt% initial solid concentration, no added salt, 1.0 cm initial bed height and 5.5 V applied voltage. After about 60 minutes a bed with an average solid content of 66 wt% was obtained, see Fig. 3-22a. The final percent of water removed was 59%. The variation of current with time for red clay, shown in Fig. 3-22b, is different from the variation for Bentonite or kaolin. The current increased to twice of its initial value and it did not decrease.

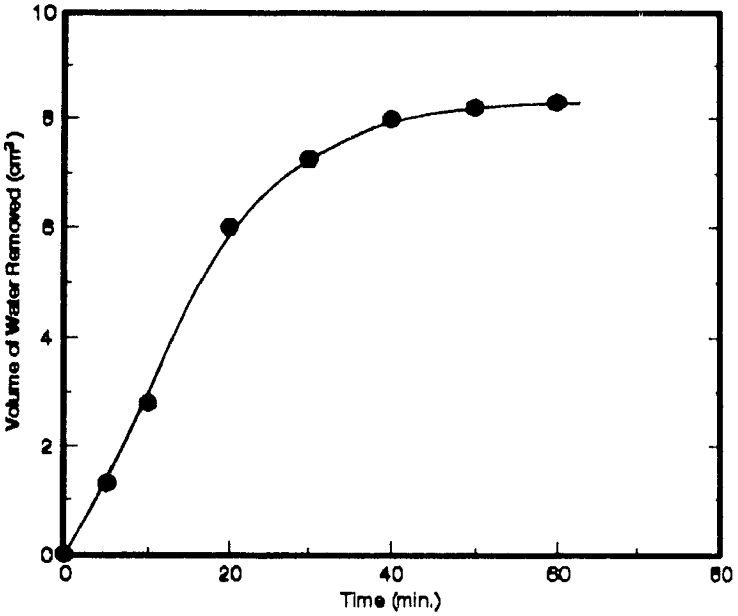


a. Volume of water removed vs. time

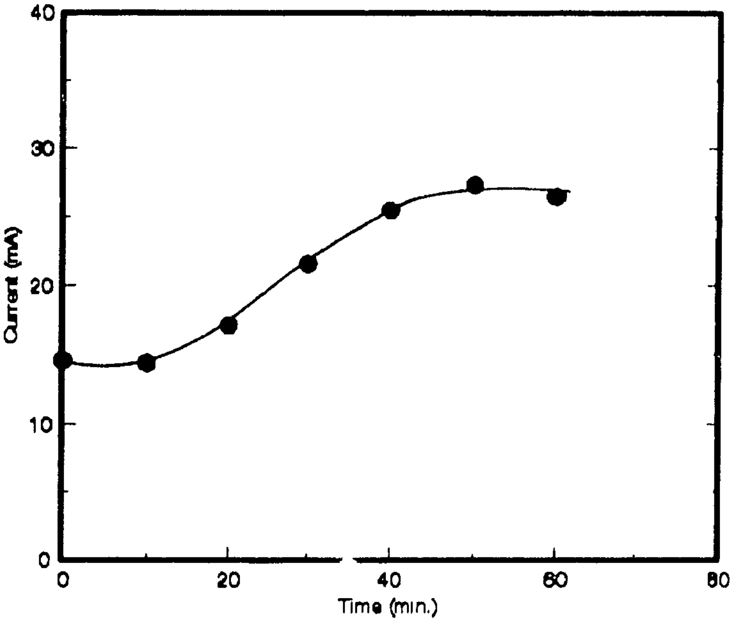


b. Current vs. time

Figure 3-21 Volume of water removed and current vs. time for kaolin under constant DC voltage. (25 wt%; 0 M; 1.0 cm; 5.0 V)



a. Volume of water removed vs. time



b. Current vs. time

Figure 3-22 Volume of water removed and current vs. time for red clay under constant DC voltage. (45 wt%; 0 M; 1.0 cm; 5.5 V)

CHAPTER 4

INTERRUPTED ELECTROOSMOTIC DEWATERING

The electroosmotic dewatering of Bentonite suspensions under interrupted DC voltage and current was studied experimentally; as well a few runs were carried out with kaolin and red clay for comparison. The interrupted EOD results are reported in this chapter and compared to EOD under constant current or voltage.

4.1 General Features of Interrupted Electroosmotic Dewatering

In interrupted dewatering a constant current or voltage is applied for t_1 seconds followed by a period of t_2 seconds when the power supply is turned off. This pattern is repeated throughout dewatering. During off-period, there is either a short circuit or an open circuit. Interrupted EOD with a short circuit is denoted "IS"; with an open circuit, "IO". During the on-time, t_1, there is either constant voltage or constant current. Interrupted EOD introduces two new variables: the on-time, t_1, and the off-time, t_2. For each experiment the following data were recorded as functions of time: the volume of water removed and the current in the interrupted applied voltage experiments and the overall voltage drop in the interrupted current experiments.

For two constant voltage experiments, one DC and one IS, the results of three replicates are presented in Fig. 4-1 for 2.75 V applied voltage, 1.0 cm initial bed height, 9.1 wt% initial solid content and no $CaCl_2$. The time intervals for the IS experiments were 30 s for the on period and 0.5 s for the off period, denoted as

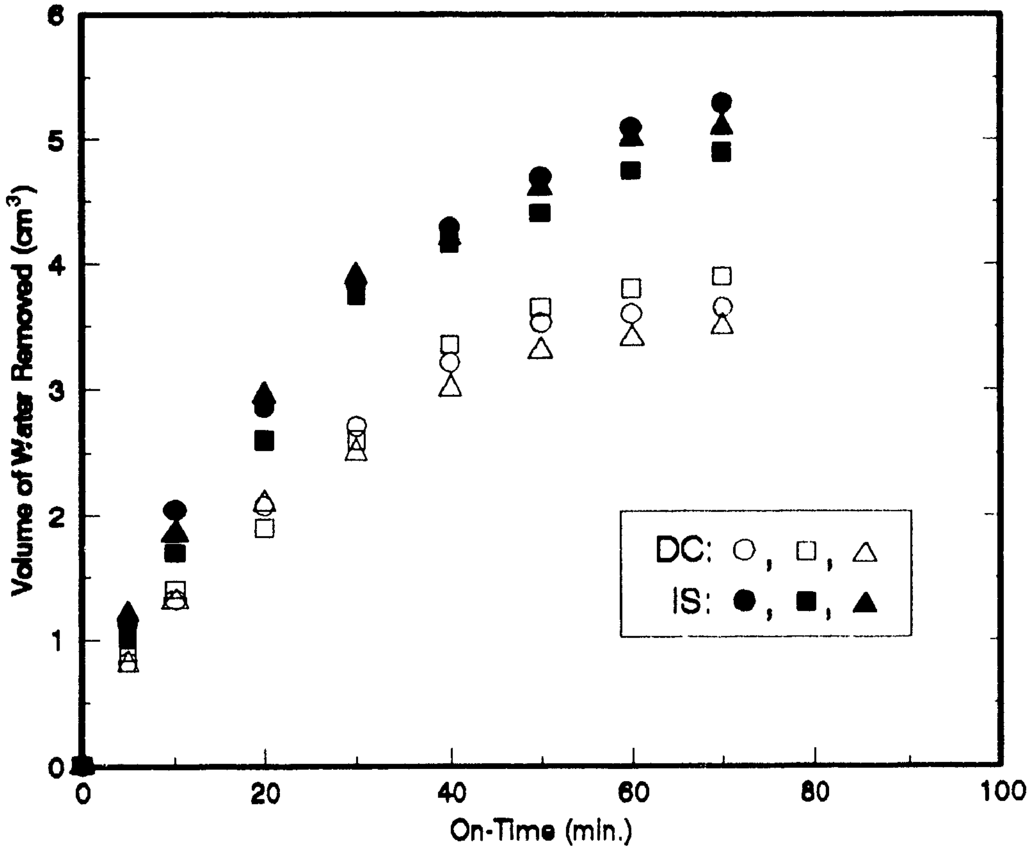


Figure 4-1 Volume of water removed vs. on-time for Bentonite under DC and IS (30/0.5). Data from three replicate runs. (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

30/0.5. Figure 4-1 shows the volume of water removed as a function of on-time. For DC, on-time is the same as running time. For IS, on-time is the time that the power was applied to the electrodes. For equal on-times more water was removed by IS than DC. After 70 minutes, about 26% of the initial water was removed by IS compared to about 18% by DC. Replicate data in Fig. 4-1 show good agreement, with the maximum deviation of the data from the average value of approximately ±5.5% for IS and ±4% for DC.

During the off-time the short circuit was applied through a 0.2 Ω resistor. This resistance, which was negligible compared to the 60 to 100 Ω resistance of the bed, was used so that the transient current could be measured during off period. When a higher resistance of 0.5 Ω was used, there was no change in the current, thus it seems that the present data are similar to those which would be obtained with a true short circuit (0 Ω).

Figures 4-2, 4-3 and 4-4 show the variation of current as a function of time during one cycle for IS, at the start, after 20 minutes and after 60 minutes of dewatering, respectively The voltage for the first 30 s (on-time) was 2.75 V and then for 0.5 s was zero (off-time). Initially the current was about 50 mA and then dropped to 12 mA During off-time the current went to -60 mA and increased to -27 mA before the power was reapplied. After the first cycle the maximum current was less than 50 mA, around 35 mA. The variation of the current in each cycle after the first one was similar (compare Figs. 4-3 and 4-4).

To determine the variation of mean current supplied to the electrodes, the current/time data were integrated assuming zero current during the off-time. These data for IS and the variation of current in the DC run are presented in Fig. 4-5 as

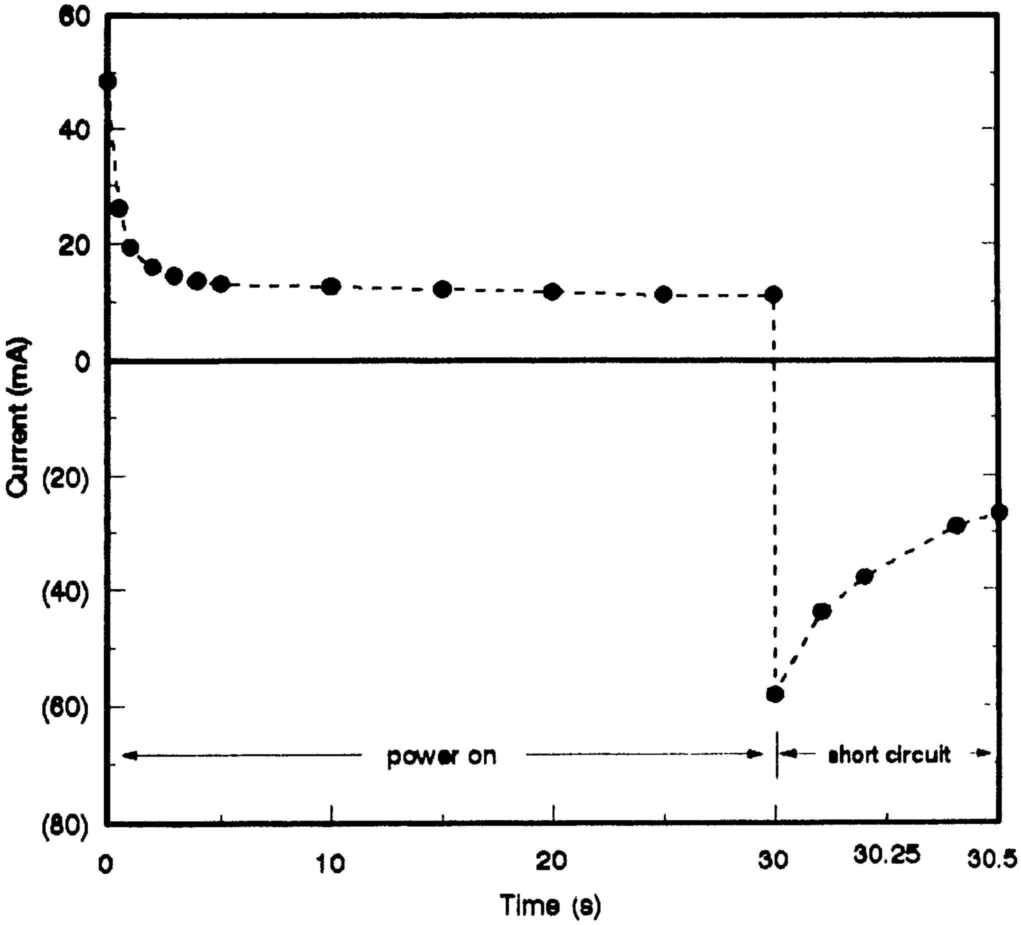


Figure 4-2 Variation of current with time at the start of dewatering for Bentonite under IS (30/0.5). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

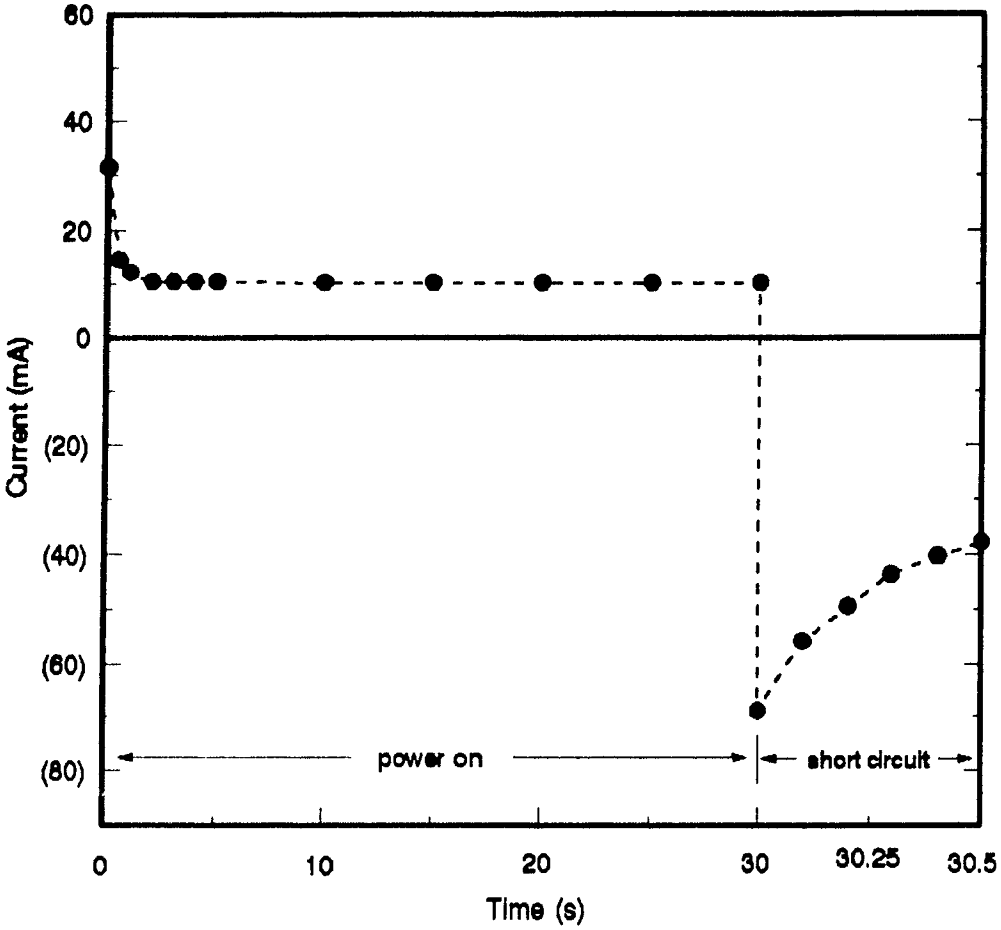


Figure 4-3 Variation of current with time after 20 minutes of dewatering for Bentonite under IS (30/0.5). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

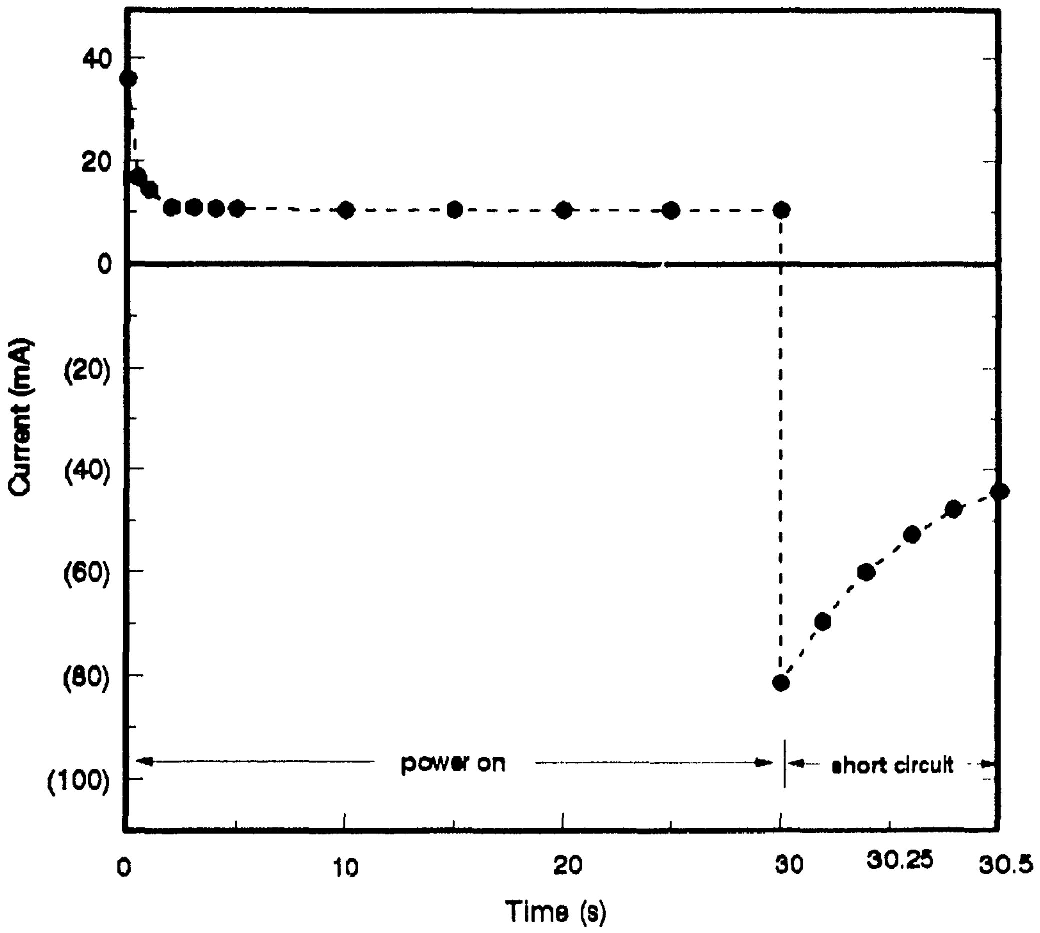


Figure 4-4 Variation of current with time after 50 minutes of dewatering for Bentonite under IS (30/0.5). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

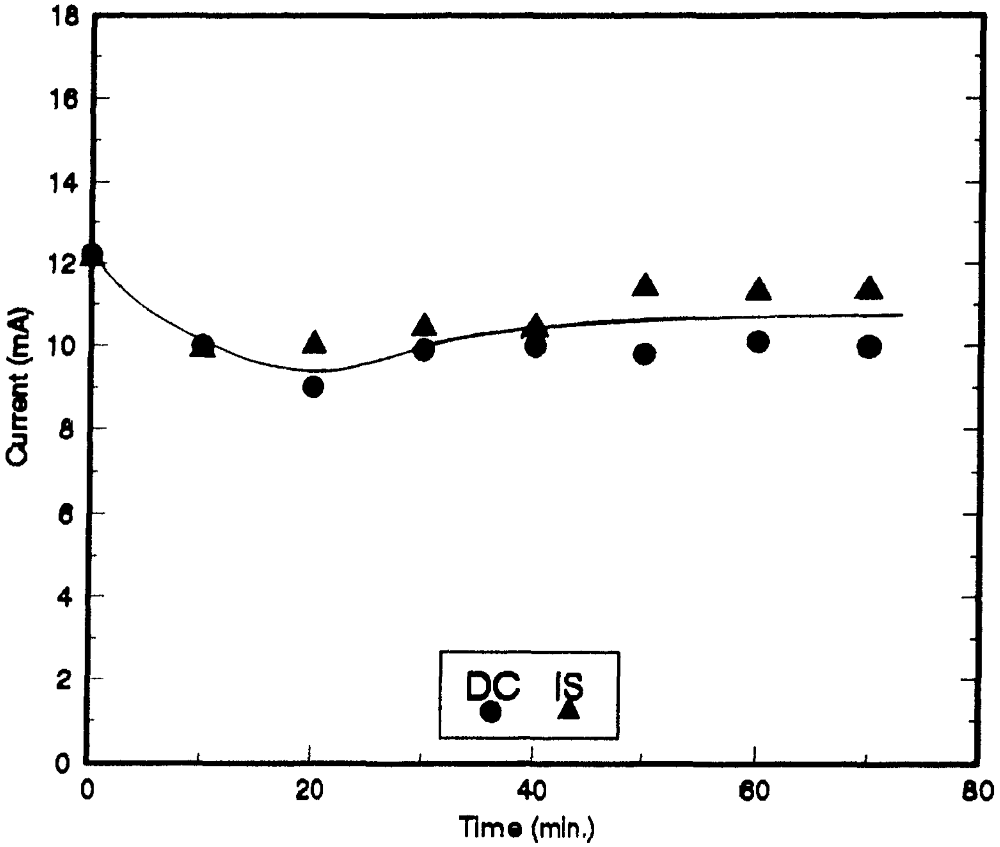


Figure 4-5 Variation of mean current with time for Bentonite under DC and IS (30/0.5). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

the average ofwhree replicates for each process. Nearly the same mean current was passed in both cases. Since the applied voltage was low, there was no maximum current- see section 3.2.

4.2 Comparison of Short Circuit with Open Circuit

Two types of interrupted processes were studied: a short circuit during the off-time (IS) and an open circuit during the off-time (IO). Figure 4-6 shows the volume of water removed as a function of on-time for DC, IS and IO for an initial concentration of 9.1 wt% Bentonite with no added electrolyte, an initial height of 1.0 cm and a constant voltage of 2.75 V. For both interrupted processes the power was on for 30 s and off for 0.5 s (30/0.5) to give a frequency of 0.033 Hz and 98.4% on-time. The volume of water removed was essentially the same for DC and IO, but more water was removed by IS. The final water removals were 18, 19 and 26% for DC, IO and IS, respectively. Figure 4-7 shows similar results for an initial height of 2.0 cm and an applied voltage of 5.5 V. The DC, IO and IS processes removed 47%, 48% and 53% of the initial water, respectively.

4.3 Effect of off-time on IS

Figures 4-8 through 4-16 show the effects of off-time intervals on IS. The on-time was 30 s with off-times of 0.5, 3 and 20 s. All data except those in Figs. 4-10 and 4-12 are for an initial height of 1.0 cm, 9.1 wt% initial solid content with no electrolyte. The data in Fig. 4-10 are for a 1.0 cm height of distilled water or $CaCl_2$ solution with 10^{-3} or 10^{-2} M concentration, i.e. there was no solid in the column The bottom of the columns under the lower electrode was sealed with a plastic sheet

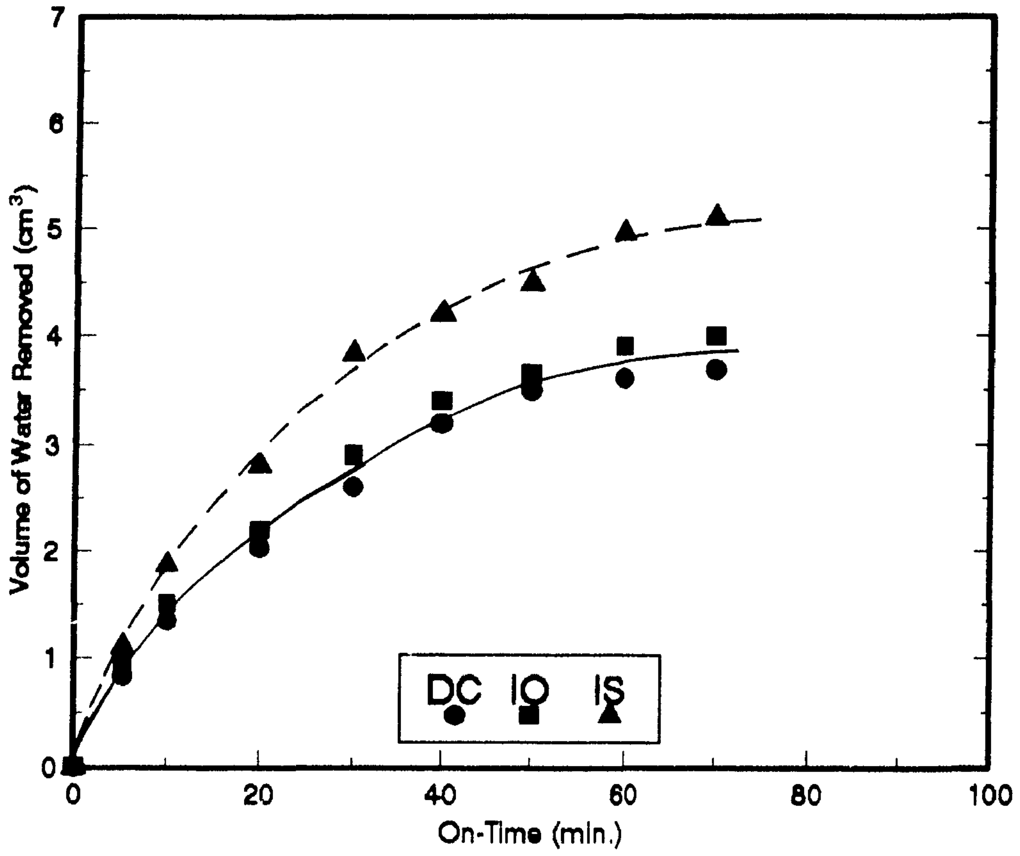


Figure 4-6 Volume of water removed vs. on-time for Bentonite under DC, IO (30/0.5) and IS (30/0.5). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

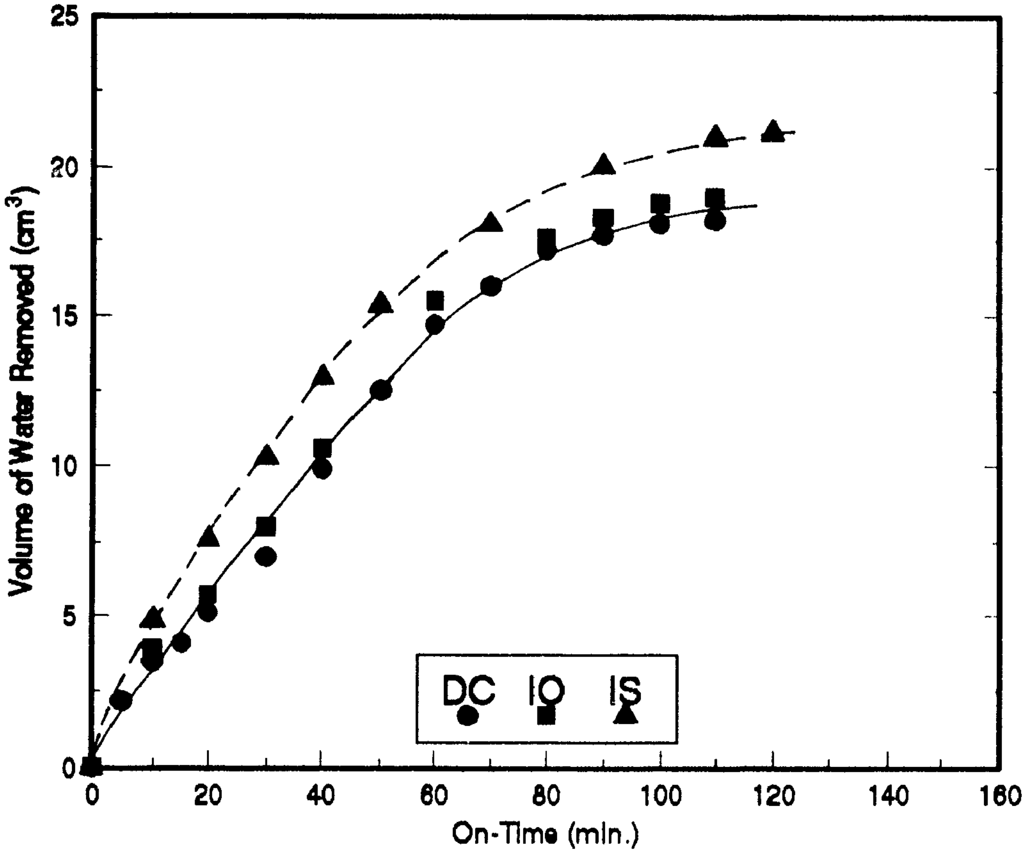


Figure 4-7 Volume of water removed vs. on-time for Bentonite under DC, IO (30/0.5) and IS (30/0.5). (9.1 wt%; 0 M; 2.0 cm; 5.5 V)

The applied voltage for all runs was 2.75 V. Figure 4-8 shows the volume of water removed as a function of on-time for DC and for three off-times. The amount of water removed decreased as the off-time increased. The final percent of water removed was 18, 26, 21 and 13.1% for DC and off-times of 0.5 s, 3 s and 20 s, respectively

Figures 4-9 and 4-10 show the variation of the current for IS (30/20) at the start of dewatering and after 20 minutes. The data are similar to those in Figs. 4-2 to 4-4 for IS with 0.5 s off-time. Figure 4-11 shows similar data for the columns of distilled water, 10^{3} and 10^{2} M $CaCl_2$ solutions. The current-time traces for the liquid columns remained the same for all on-off cycles. The current variation was similar to that for a bed of Bentonite suspension. Figures 4-12 and 4-13 show current-time data for IS (30/3) at the start and after 20 minutes of dewatering.

For Bentonite suspensions, the maximum current for the second and subsequent on-times was larger for longer off-times. For IS (30/20) the maximum current after the first cycle was about 70 mA while it was about 45 mA and 35 mA for the IS (30/3) and IS (30/0.5), respectively. Since the initial conditions were the same for all three IS experiments, the variation of current during on-time for the first cycle was similar.

The minimum current for Bentonite suspensions, between -80 and -55 mA, occurred when the electrodes were short circuited. For IS (30/20) the current nearly reached zero during the short circuit time. For IS (30/3), the current reached about -20 mA while for IS (30/0.5) it reached -40 mA during short circuit. Figure 4-14 shows the data plotted as the mean current against time. There was relatively little difference between the mean currents in DC and IS.

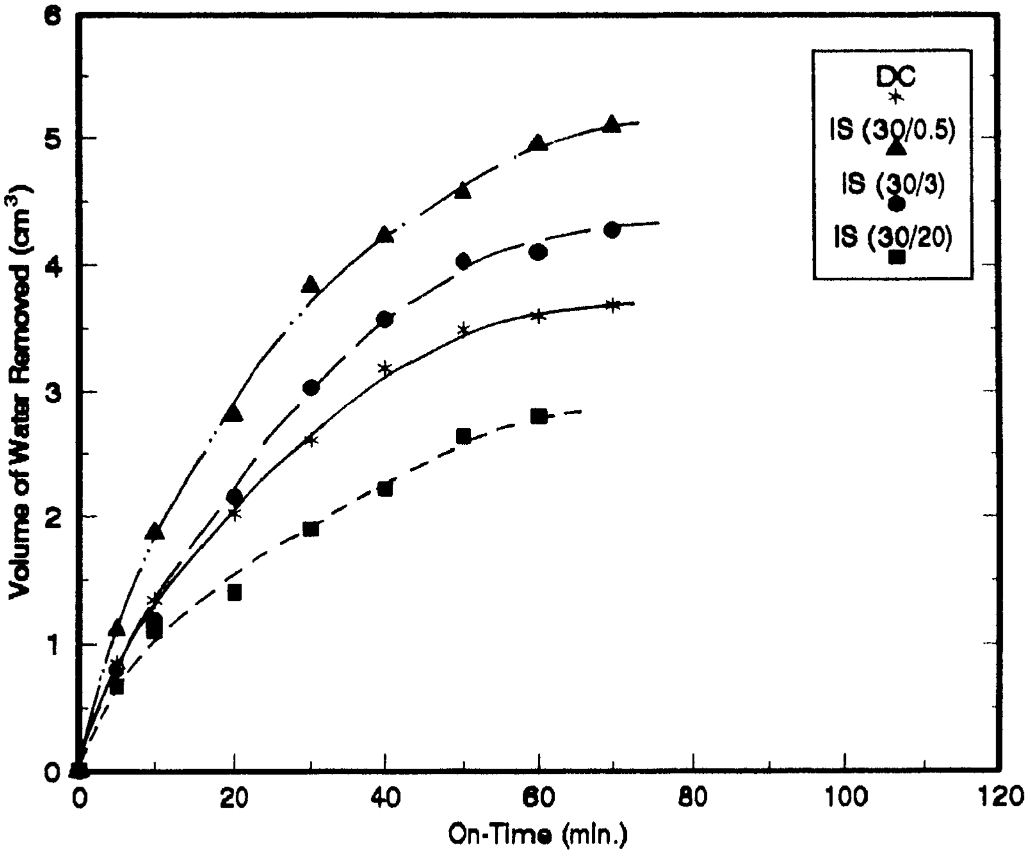


Figure 4-8 Volume of water removed vs. on-time for Bentonite under DC and IS (30/0.5, 3, 20). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

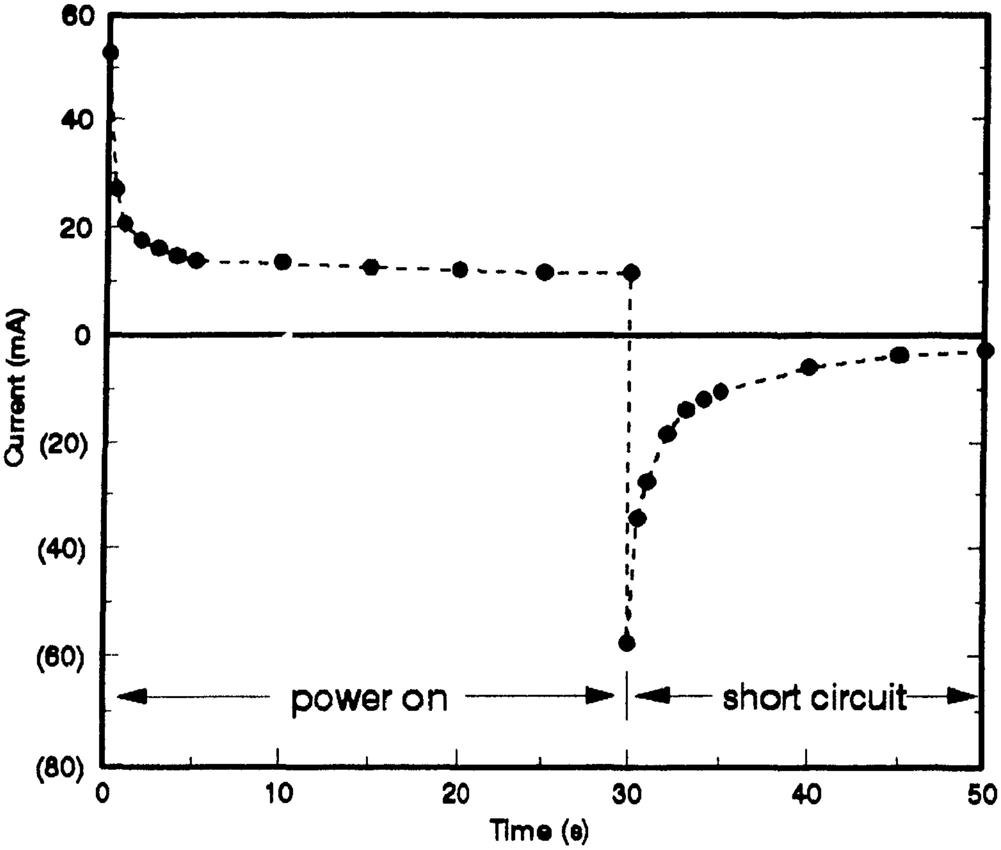


Figure 4-9 Variation of current with time at the start of dewatering for Bentonite under IS (30/20). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

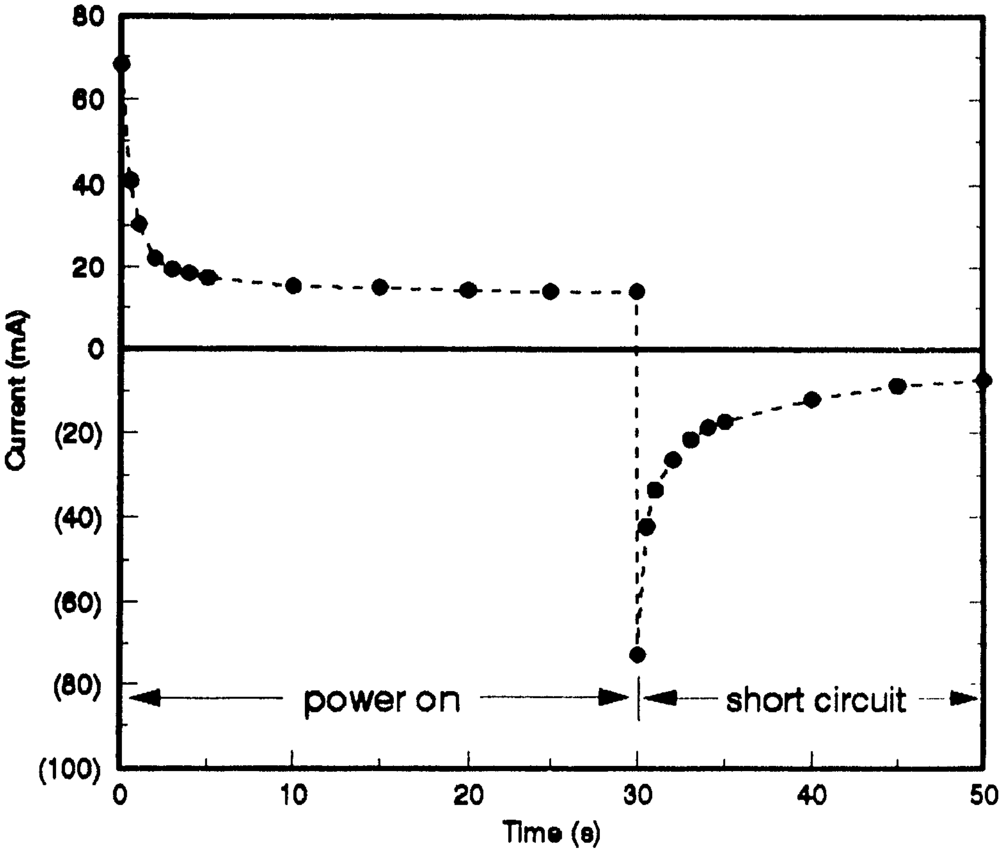


Figure 4-10 Variation of current with time after 20 minutes of dewatering for Bentonite under IS (30/20). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

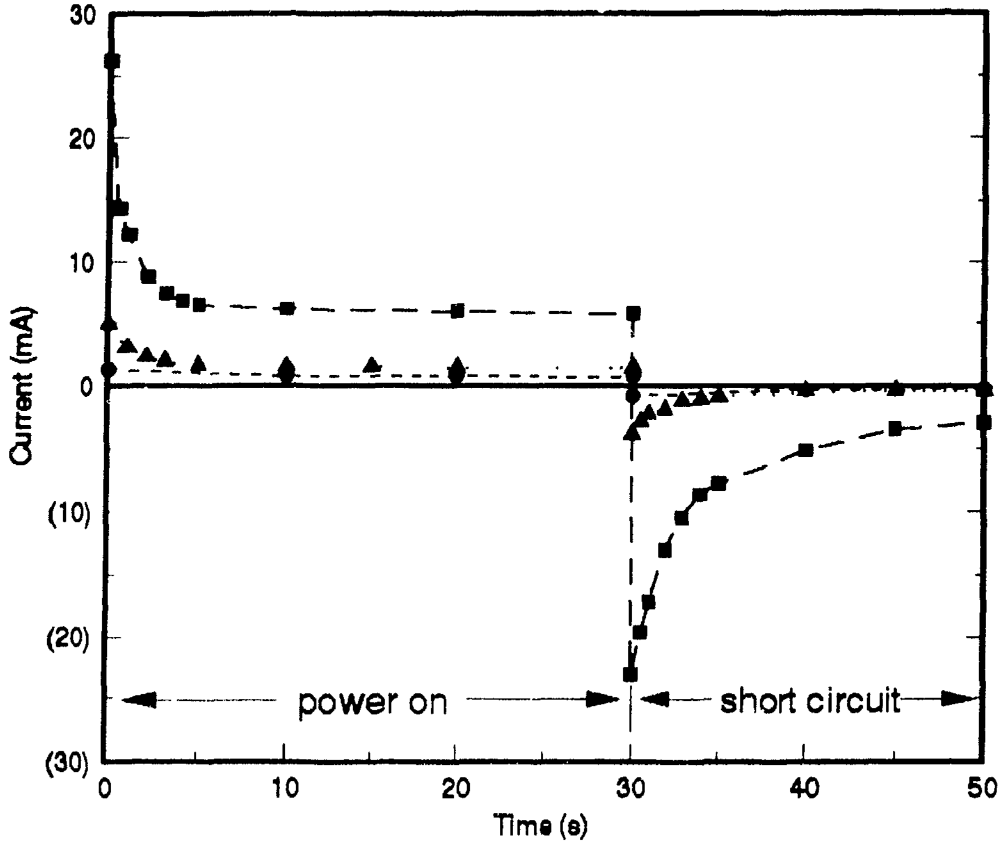


Figure 4-11 Variation of current with time after 20 minutes of dewatering under IS (30/20), • distilled water, ▲ 10^{-3} M $CaCl_2$, ■ 10^{-2} M $CaCl_2$. (1.0 cm; 2.75 V)

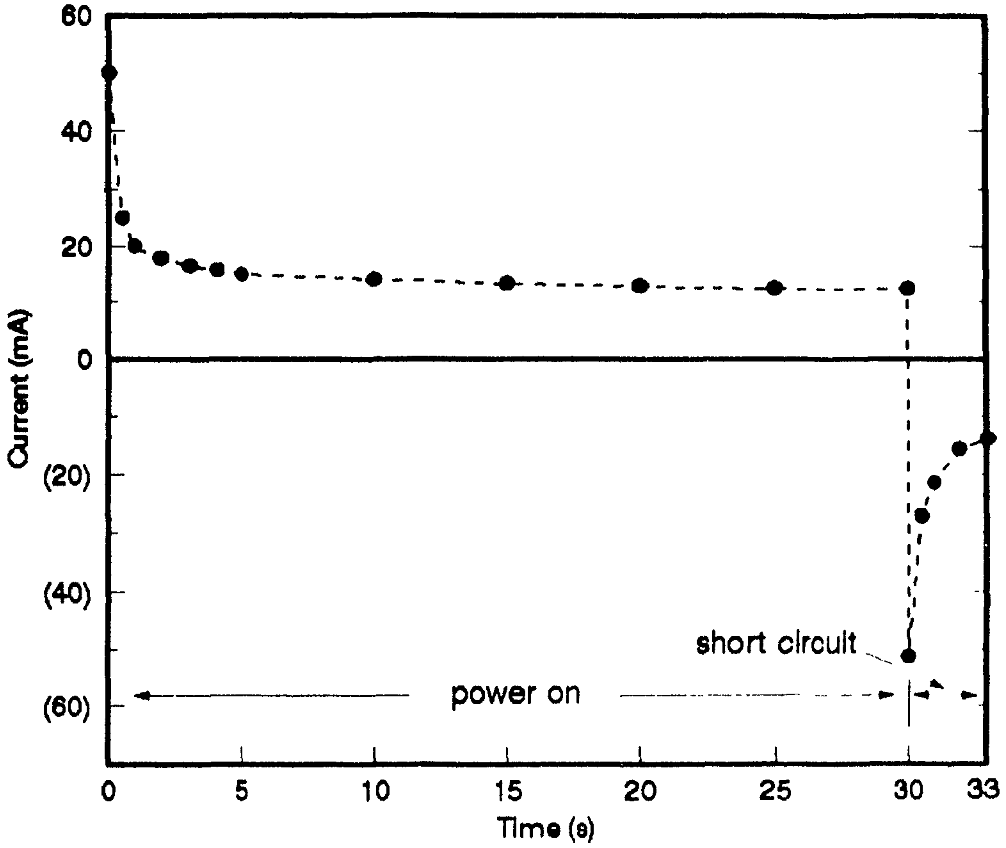


Figure 4-12 Variation of current with time at the start of dewatering for Bentonite under IS (30/3). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

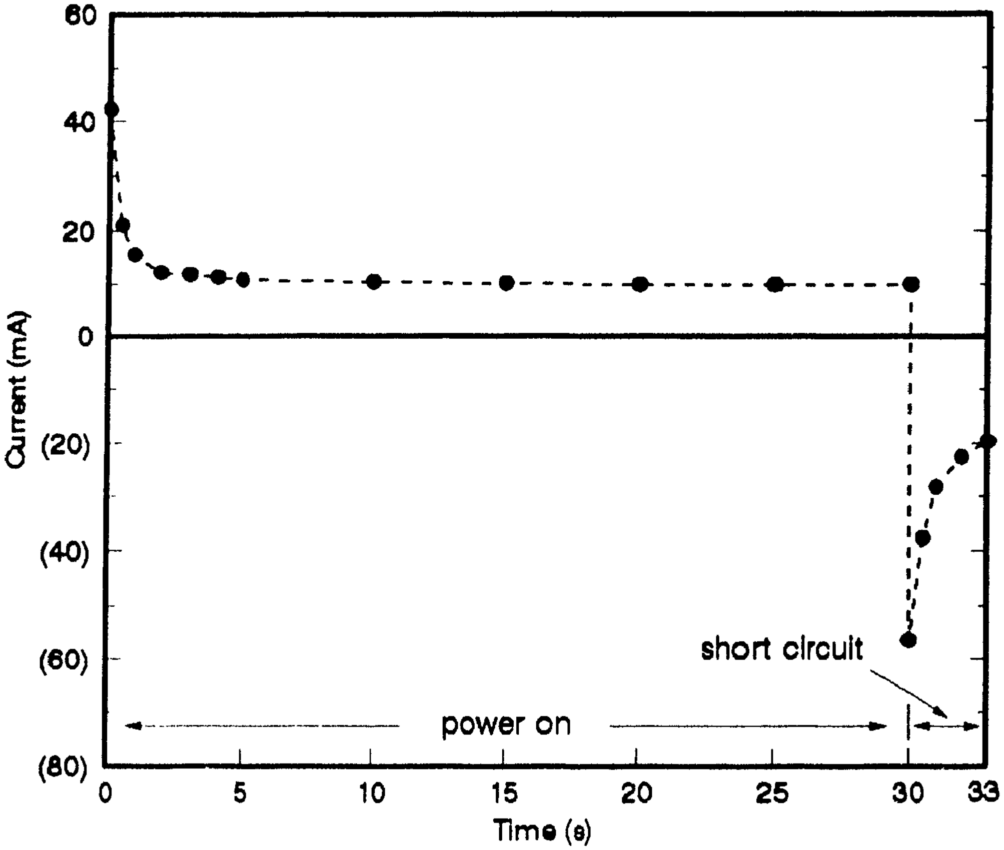


Figure 4-13 Variation of current with time after 20 minutes of dewatering for Bentonite under IS (30/3). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

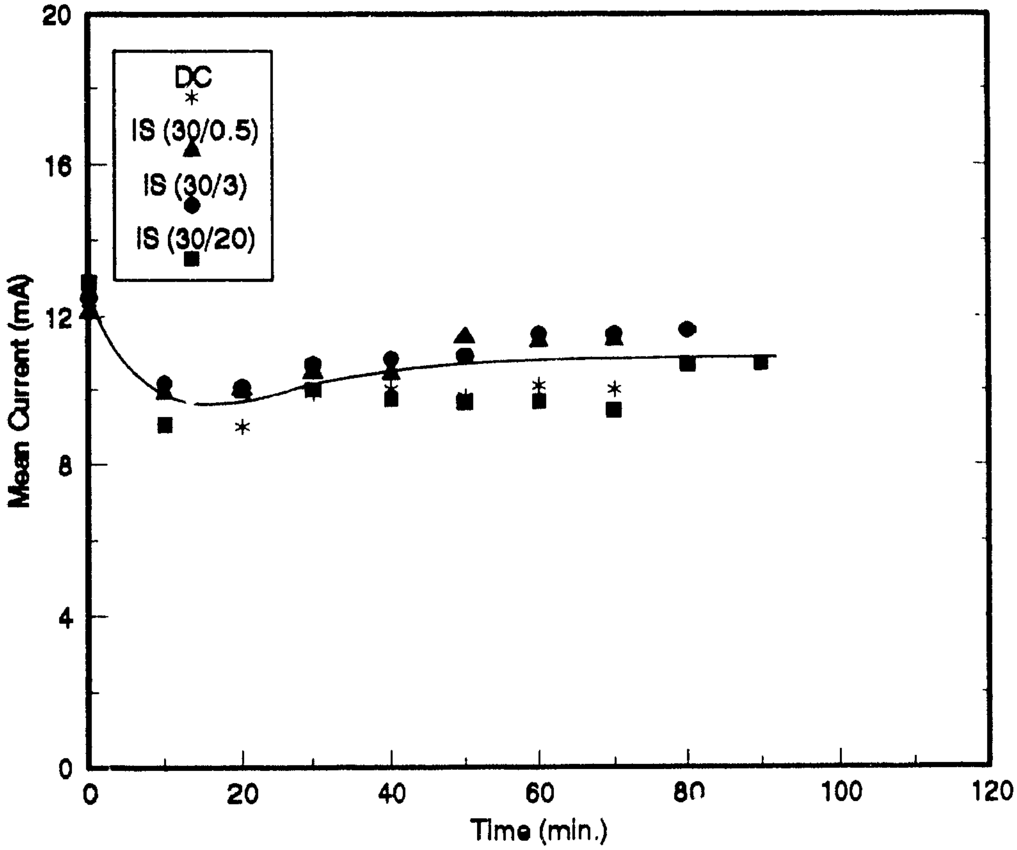


Figure 4-14 Variation of mean current with time for Bentonite under DC and IS (30/0.5, 3, 20). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

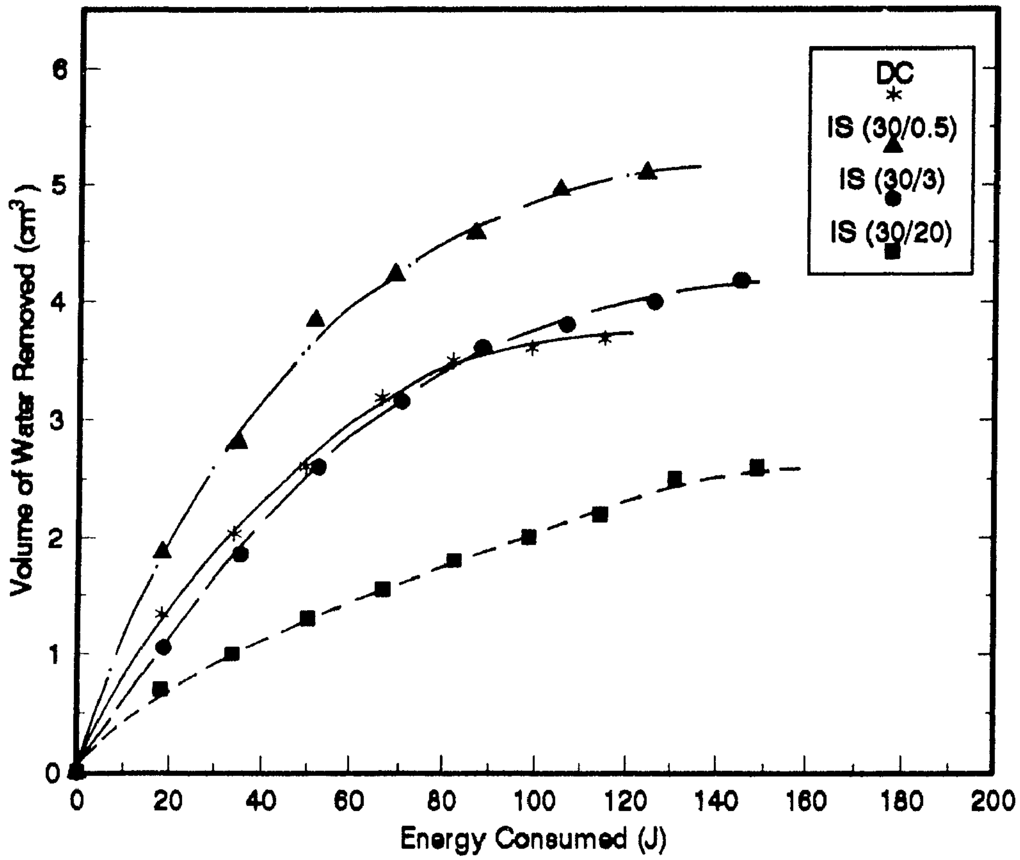


Figure 4-15 Volume of water removed vs. energy consumption for Bentonite under DC and IS (30/0.5, 3, 20). (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

Figure 4-15 shows the volume of water removed as a function of energy consumption. For equal energy consumption IS (30/0.5) removes about 20-30% more water than DC. The water removal for IS (30/3) is close to that for DC except near the end of dewatering. Less water is removed by IS (30/20) than by DC.

4.4 Effect of Initial Bed Height

Figure 4-16 shows the effect of the initial bed height with DC and IS. In all cases the original suspensions contained 9.1 wt% Bentonite and no electrolyte. A different voltage was applied for each height. The initial overall field strength, defined as the applied voltage divided by the initial bed height, was 2.75 V/cm. The voltage applied across a bed of 1.0 cm initial height was 2.75 V, across a bed of 2.0 cm height, 5.5 V, etc. The IS (30/0.5) process was used for the interrupted runs.

Figure 4-16 shows the volume of water removed as a function of on-time for various initial bed heights. For each height there was a DC and an IS run. For the 2.0 cm initial bed height, dewatering stopped after about 46 and 53% water removal for DC and IS, respectively. Similar data for the 1.5 cm and 1.0 cm initial bed height, were about "43 and 52%" and "18 and 26%" removal, respectively. The percent increases in the final water removed by IS relative to DC were 44, 20 and 14% for the 1.0, 1.5 and 2.0 cm initial bed heights, respectively.

4.5 Effect of Salt and Solid Concentration

Figures 4-17 and 4-18 show the effect of the salt and solid concentration on dewatering using DC and IS (30/0.5). All data are for an initial height of 1.0 cm and a voltage of 2.75 V.

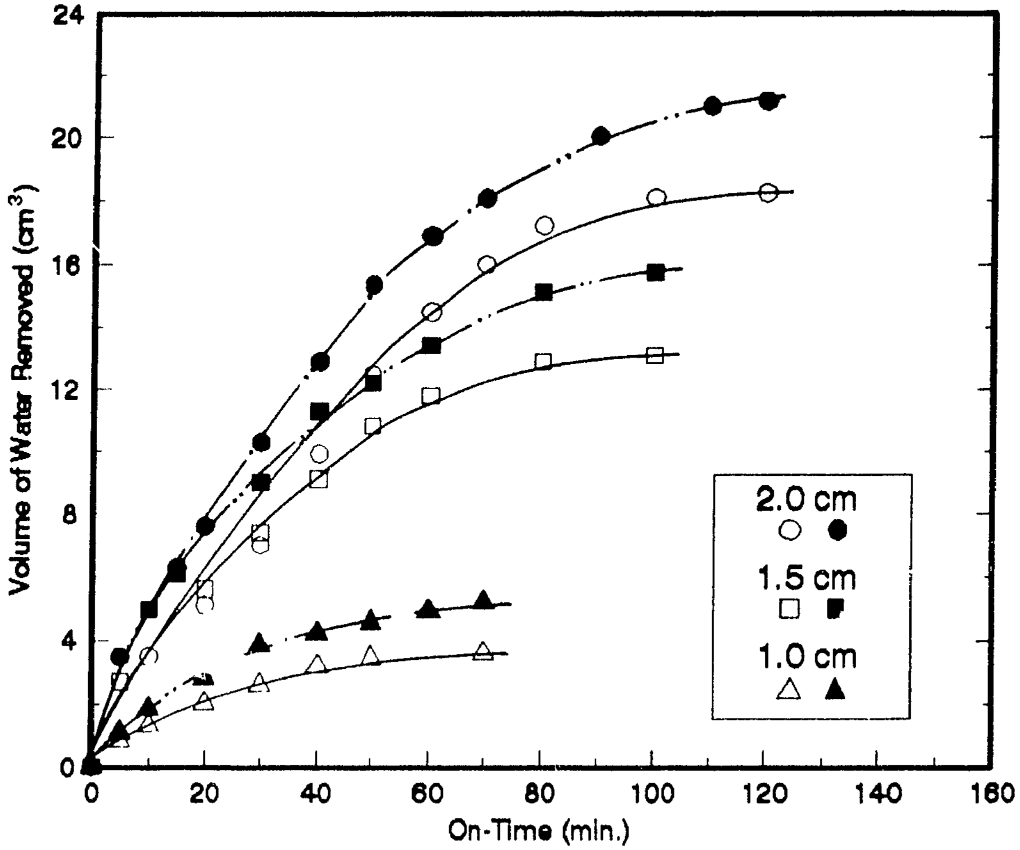


Figure 4-16 Volume of water removed vs. on-time for Bentonite with an initial overall field strength of 2.75 V/cm. Open symbols refer to DC; filled symbols refer to IS (30/0.5). (9.1 wt%; 0 M)

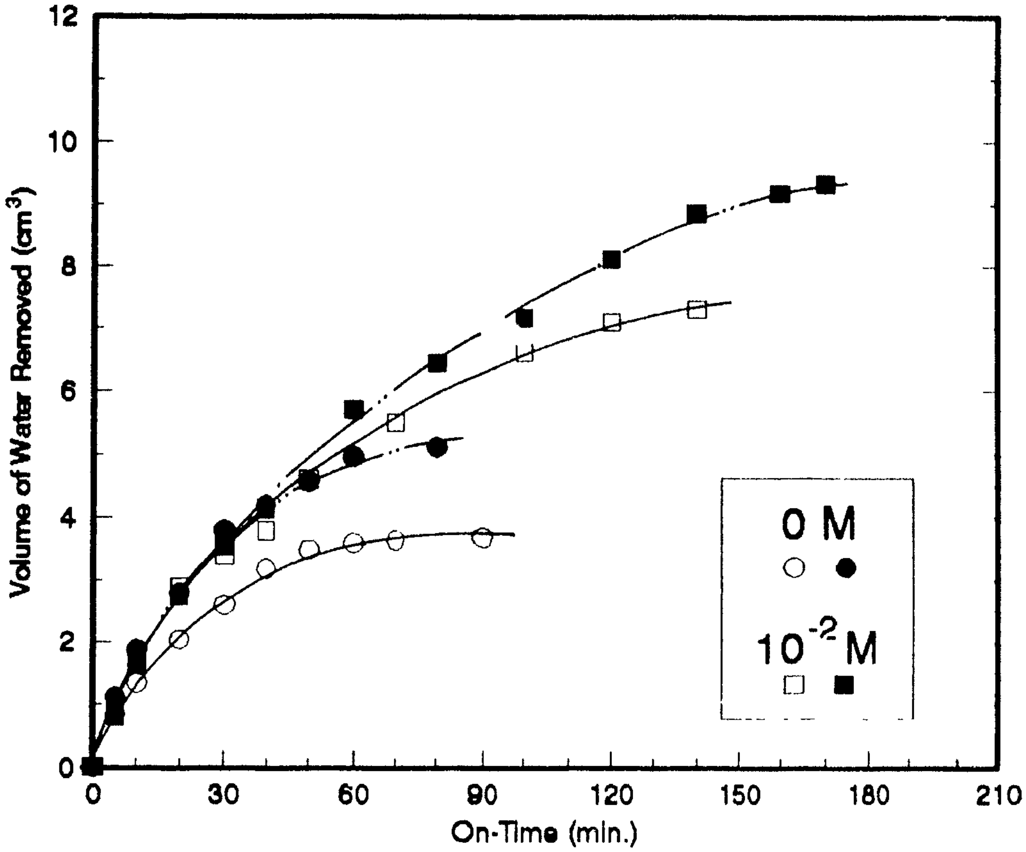


Figure 4-17 Volume of water removed vs. on-time for Bentonite. Open symbols refer to DC; filled symbols refer to IS (30/0.5). (9.1 wt%; 1.0 cm; 2.75 V)

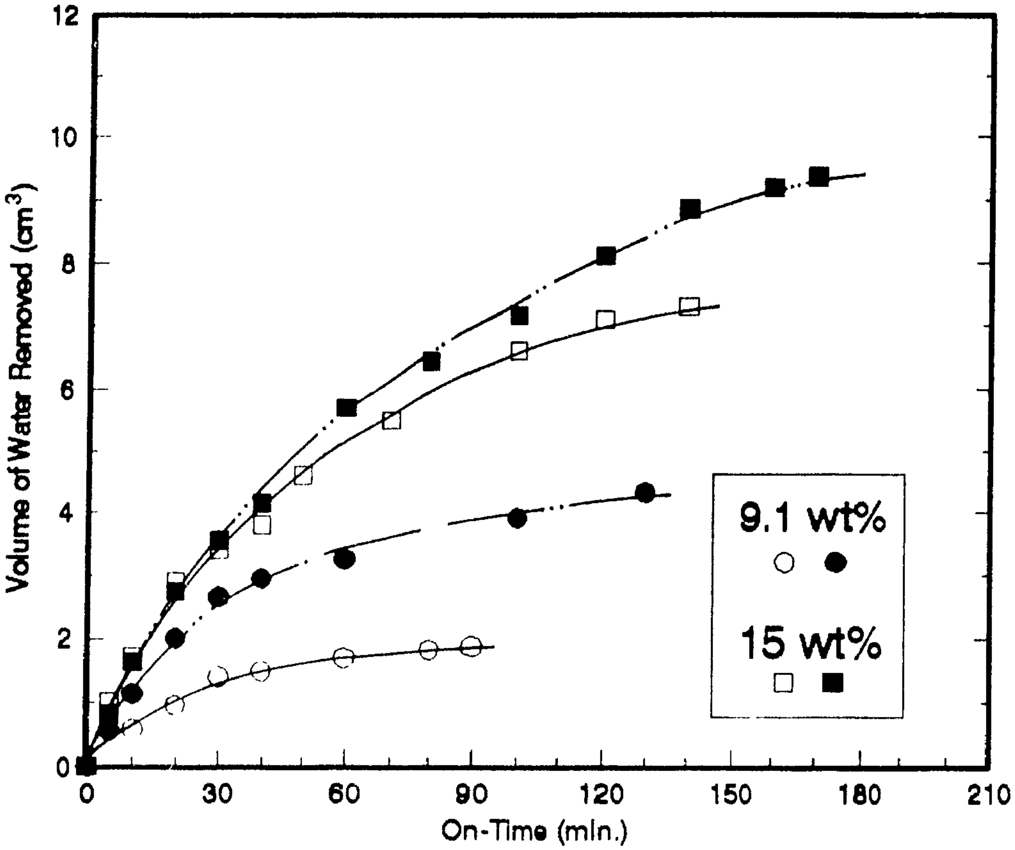


Figure 4-18 Volume of water removed vs. on-time for Bentonite. Open symbols refer to DC; filled symbols refer to IS (30/0.5). (0.01 M; 1.0 cm; 2.75 V)

In Fig. 4-17 the volume of water removed is plotted as a function of on-time for two initial salt concentrations, 0 M and 10^{-2} M $CaCl_2$ with an initial solid content of 9.1 wt% Bentonite. More water was removed by IS than by DC. With no electrolyte, 18 and 26% of initial water was removed by DC and IS, respectively. For an initial salt concentration of 10^{-2} M, DC removed 33% of the initial amount of water while IS removed 44%.

Figure 4-18 shows similar data for an initial salt concentration of 10^{-2} M $CaCl_2$ and initial solid contents of 9.1 and 15.0 wt% Bentonite. In both cases, IS removed more water than DC.

4.6 Effectiveness of IS after DC

Figure 4-19 shows the volume of water removed as a function of on-time for an initial solid content of 9.1 wt% Bentonite, an initial $CaCl_2$ concentration of 10^{-2} M, an initial height of 1.5 cm and a constant current of 30 mA. Two runs are shown: an IS (30/0.5) run and a run with DC followed by a period of IS (30/0.5). In the latter run IS was applied only after dewatering stopped under DC. As seen earlier, IS (30/0.5) removed more water than DC alone. However the application of IS (30/0.5) after dewatering stopped with DC, removed additional water over the next 40 minutes of on-time. The final water removal for the combined DC/IS run was nearly equal to that for IS alone.

Figure 4-20 is similar plot for a constant voltage of 2.75 V and 1.0 cm initial bed height. Applying IS (30/0.5) at the end of dewatering with DC, removed additional water. The final water removal for DC/IS approached that for IS

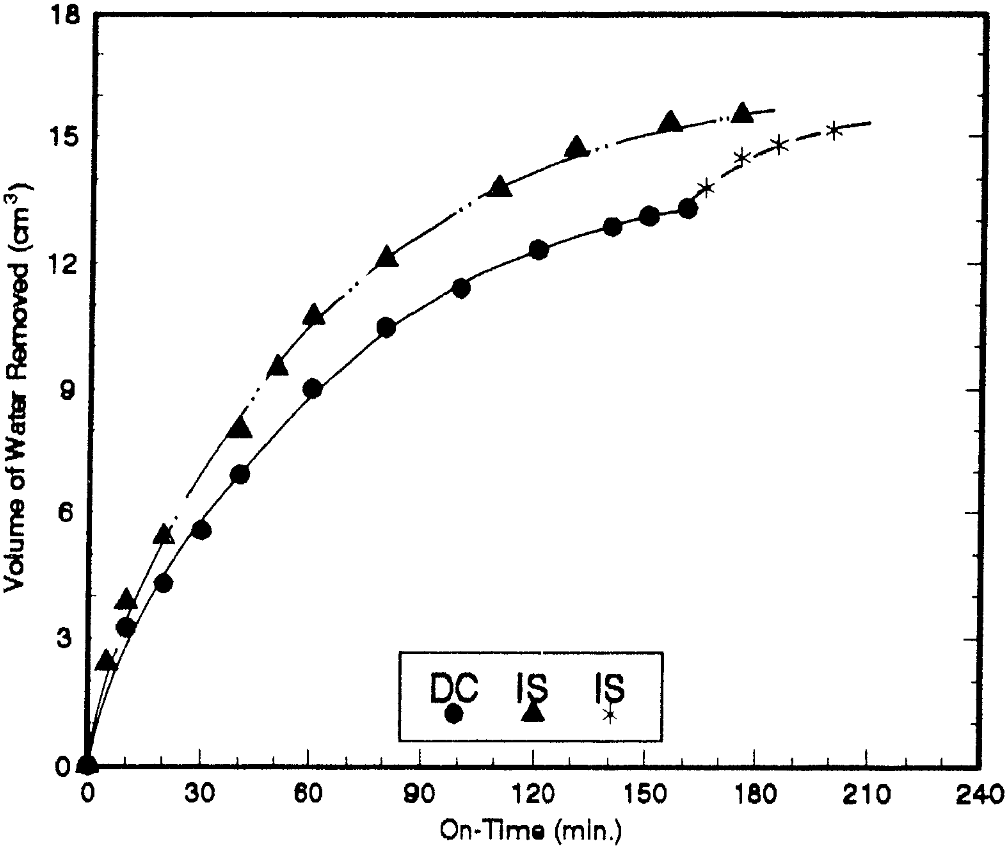


Figure 4-19 Volume of water removed vs. on-time for Bentonite under IS (30/0.5) and DC followed by IS (30/0.5). (9.1 wt%; 0.01 M; 1.5 cm; 30 mA)

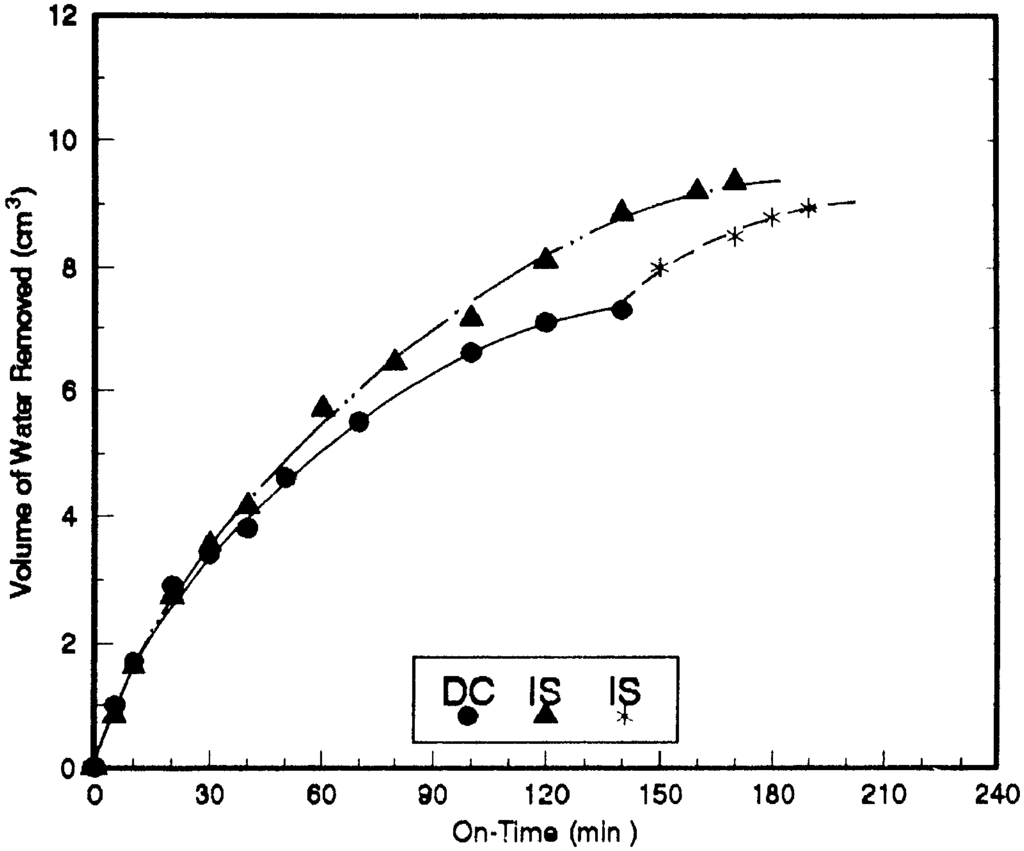


Figure 4-20 Volume of water removed vs. on-time for Bentonite under IS (30/0.5) and DC followed by IS (30/0.5). (9.1 wt%; 0.01 M; 1.0 cm; 2.75 V)

4.7 Interrupted EOD of Kaolin and Red Clay Suspensions

Figures 4-21 and 4-22 compare dewatering with DC and IS (30/0.5) for kaolin clay All data are for initial suspension of 25 wt% Kaolin with a height of 1.0 cm, no electrolyte and a voltage of 5.0 V The volume of water removed and the mean current are shown as functions of on-time in Figs. 4-21 and 4-22. The IS process increased the amount of water removed. The final percent removal for IS was 73%, yielding a bed with an average solid content of 56%. For DC the comparable figures were 62% and 46%.

Figures 4-23 and 4-24 are similar plots for red clay with 45 wt% initial solid content, no electrolyte, 1.0 cm initial bed height and 5.5 V. With IS (30/0.5), 65% of the initial water was removed compared to 59% with DC. The final average solid contents were 56 and 46 wt% for IS (30/0.5) and DC, respectively.

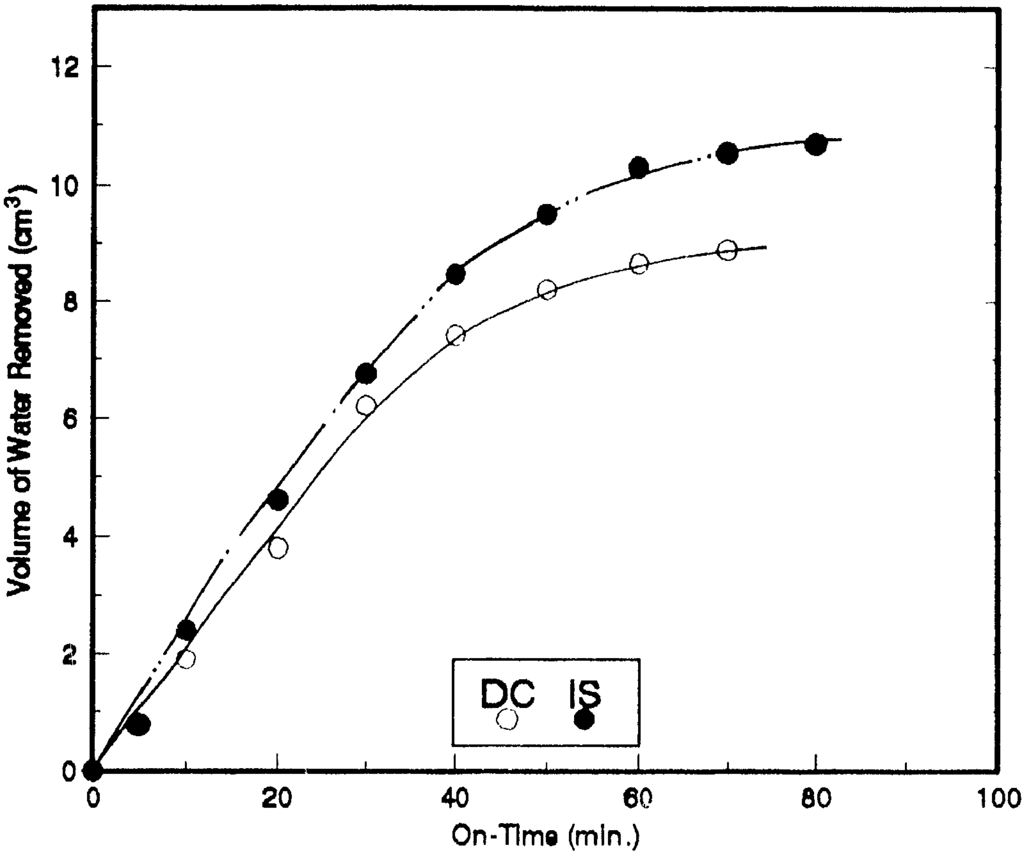


Figure 4-21 Volume of water removed vs. on-time for kaolin under DC and IS (30/0.5). (25 wt%; 0 M; 1.0 cm; 5.0 V)

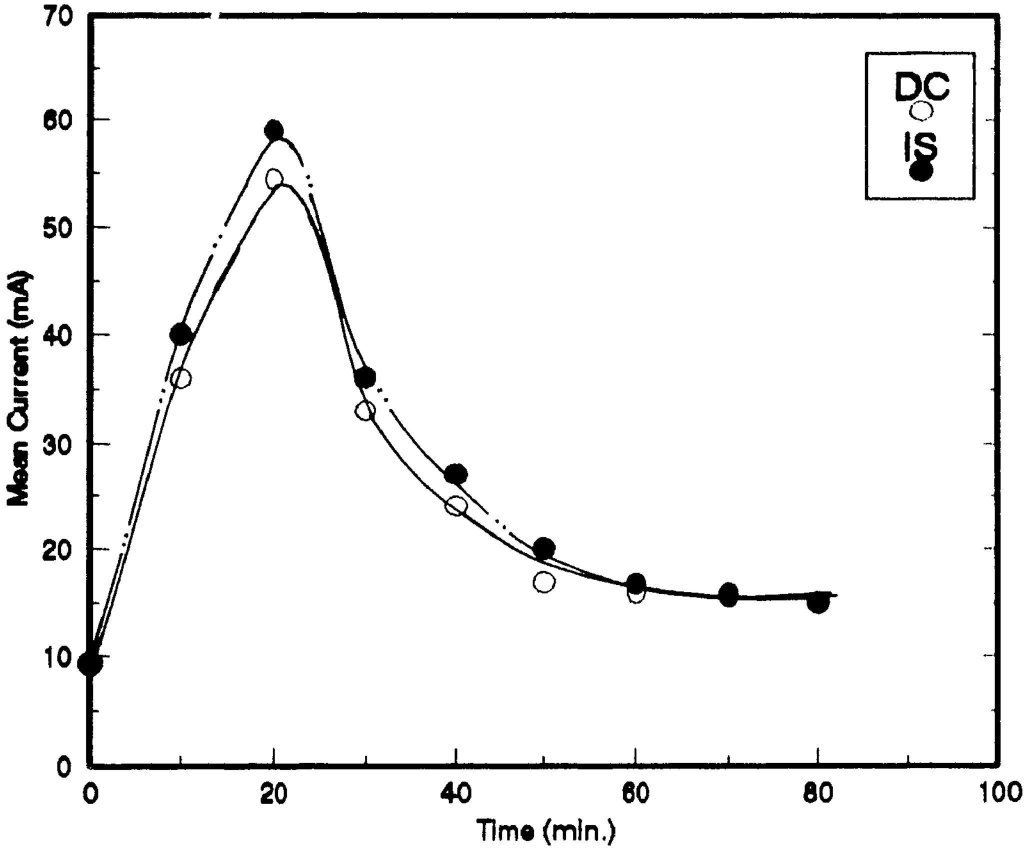


Figure 4-22 Variation of mean current with time for kaolin under DC and IS (30/0.5). (25 wt%; 0 M; 1.0 cm; 5.0 V)

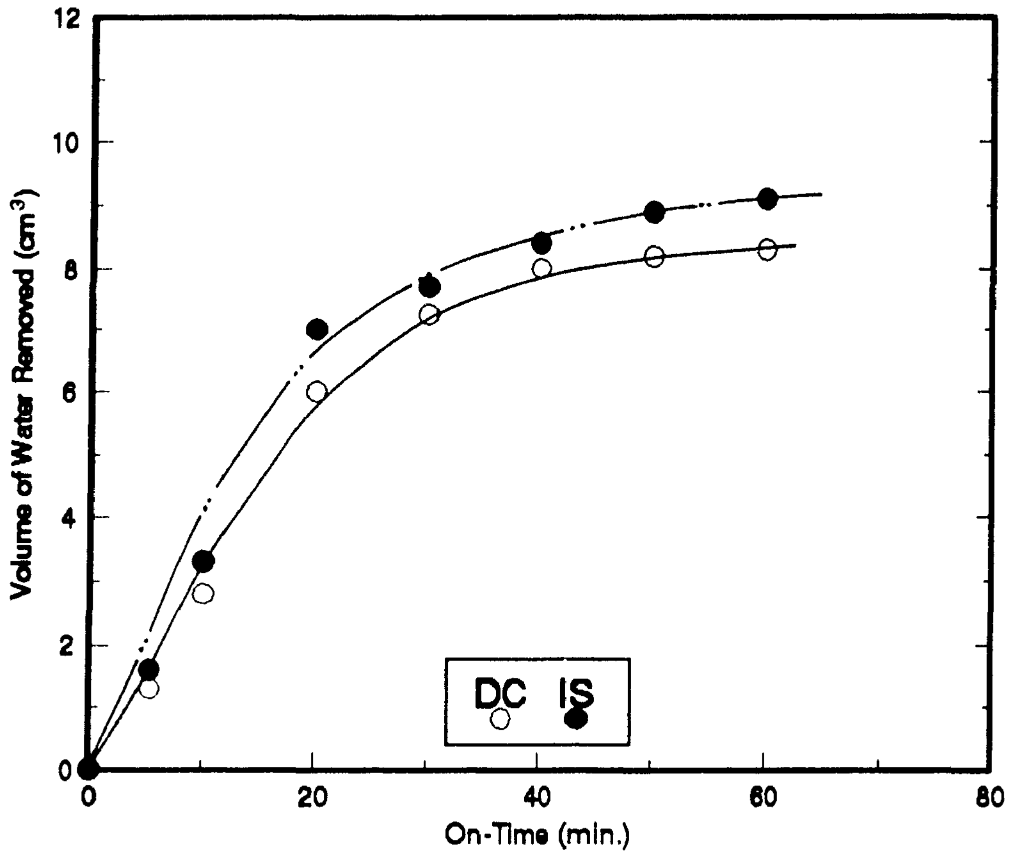


Figure 4-23 Volume of water removed vs. on-time for red clay under DC and IS (30/0.5). (25 wt%; 0 M; 1.0 cm; 5.0 V)

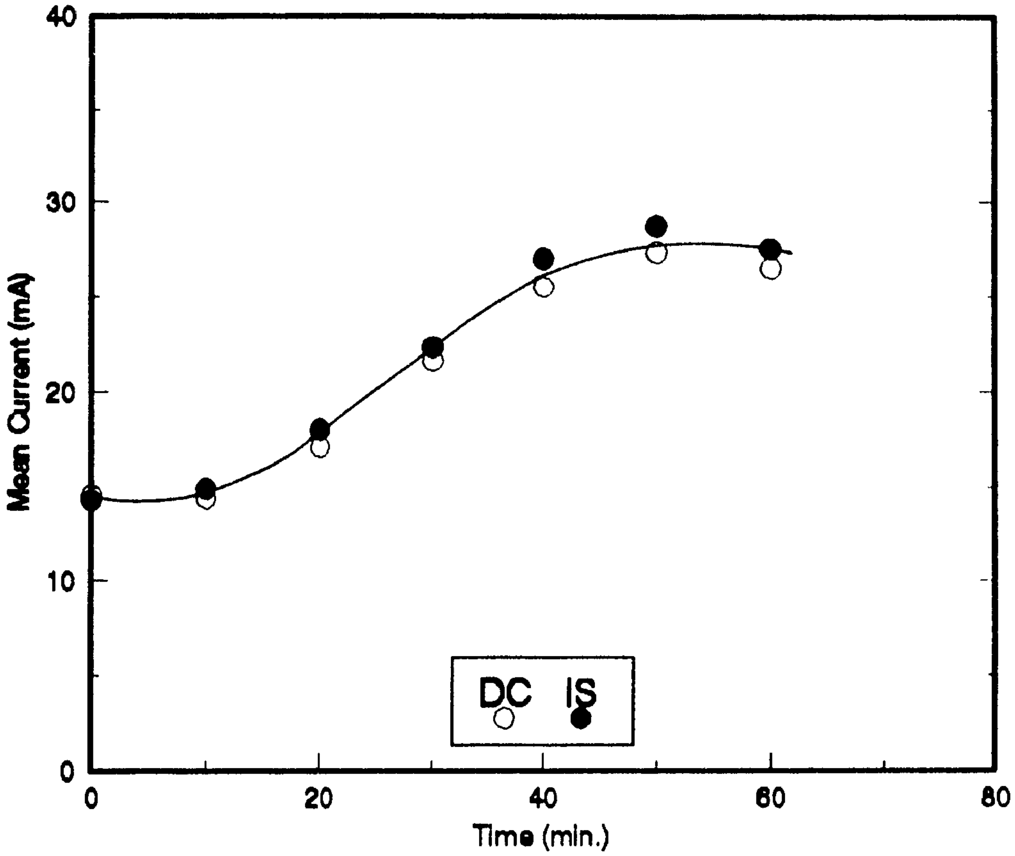


Figure 4-24 Variation of mean current with time for red clay under DC and IS (30/0.5). (25 wt%; 0 M; 1.0 cm; 5.0 V)

CHAPTER 5

DISCUSSION

In the experiments with Bentonite, kaolin or red clay suspensions as well as the experiments with distilled water or $CaCl_2$ solutions, a potential remained across the bed when the power was turned off. This potential ranged from 1.8 to 2.3 V with the upper electrode (the anode during the on-time) having a higher potential than the lower electrode (the cathode during the on-time). In some runs with Bentonite suspensions the pH values near the electrodes were measured at the end of dewatering and a difference of about 8 units of pH was observed with the lower electrode having the higher pH. The following section suggests an explanation for the presence of the potential during the off-time.

5.1 Platinum Electrodes

Each electrode was coated with platinum (see section 2.1). The performance of platinum electrodes in reactions involving liberation of gases is affected by the tendency of the electrode to develop surface oxide films when anodized. The presence of oxide films on platinum anodes was confirmed by Lingane who found that both PtO and PtO_2 are present (Anson and Lingane, 1957). Following a rapid initial oxidation, a further continuous and essentially linear increase in surface oxidation with increase in anodic potential takes place. A considerable lowering of potential is required for the reduction of the oxide film (Laitinen, 1961). Pourbaix (1974) proposed the anode potential-pH relationship shown in Fig. 5-1. The main

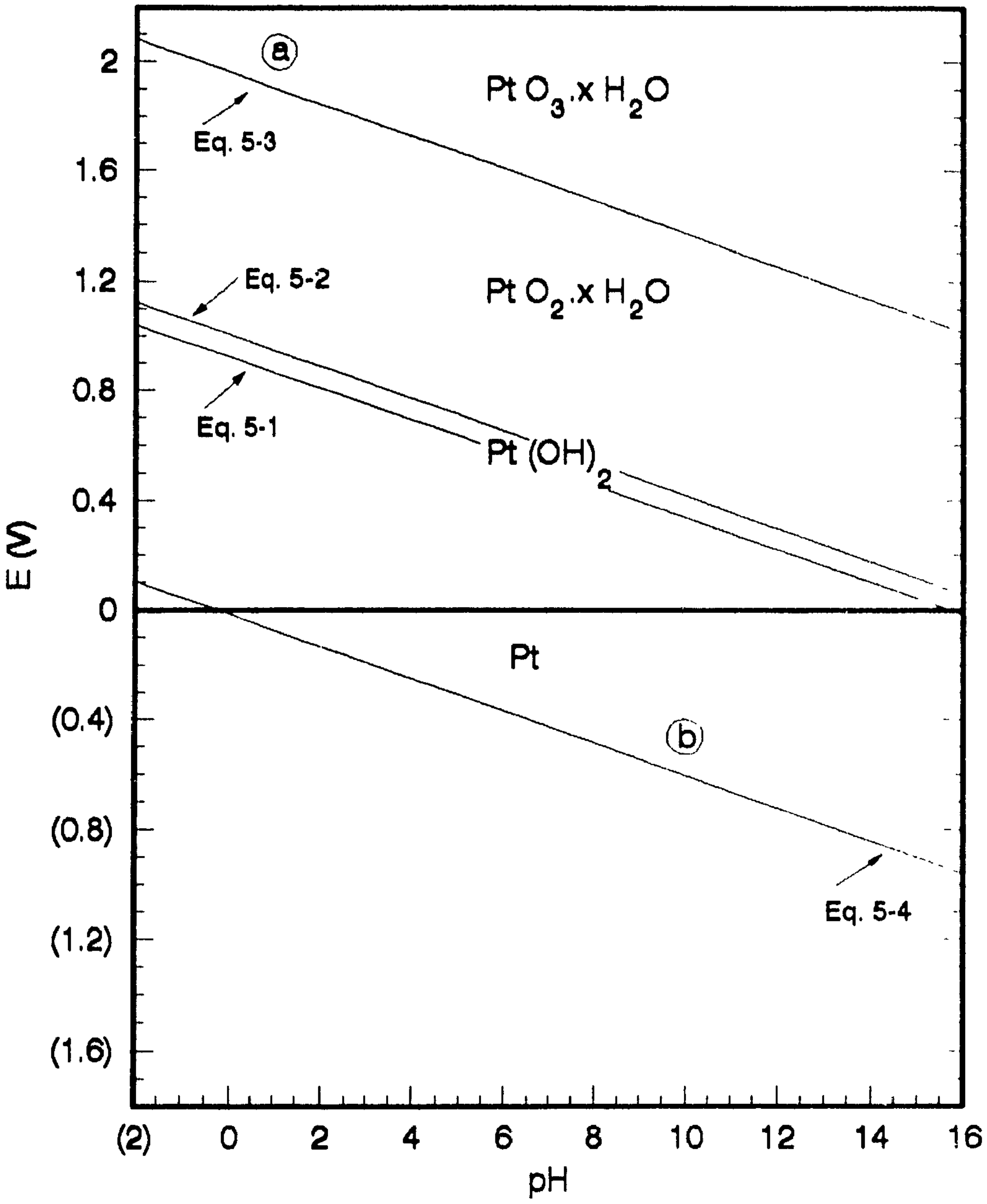


Figure 5-1 Potential-pH diagram for the platinum-water system. [Pourbaix, 1974].

species include $Pt(OH)_2$, PtO_2 and PtO_3 The electrode reactions and potentials are

$$Pt + 2H_2O \rightarrow Pt(OH)_2 + 2H^+ + 2e^- \qquad (5\text{-}1)$$
$$E_{ox} = 0.980 - 0.0591\,pH$$

$$Pt(OH)_2 \rightarrow PtO_2 + 2H^+ + 2e^- \qquad (5\text{-}2)$$
$$E_{ox} = 1.045 - 0.0591\,pH$$

$$PtO_2 + H_2O \rightarrow PtO_3 + 2H^+ + 2e^- \qquad (5\text{-}3)$$
$$E_{ox} = 2.000 - 0.0591\,pH$$

When platinum is used as an anode, it generally becomes covered with platinum oxide (PtO_2 or PtO_3 or their mixture) giving a higher potential than pure platinum at the same pH (see Fig. 5-1). When used as a cathode, platinum generally adsorbs a considerable quantity of hydrogen. Platinum is stable under the condition of potential and pH corresponding to the equilibrium state of the following reaction

$$H_2 \rightleftharpoons 2H^+ + 2e^- \qquad (5\text{-}4)$$

This reaction takes place almost reversibly on the surface of platinum (Pourbaix, 1974).

As noted earlier, the pH values were different near the electrodes with lower pH values occurring near the anode. Because of the lower pH and because of the presence of the oxide films, the anode has a higher potential than the cathode, which is either platinum or a platinum-hydrogen mixture at a higher pH (see Fig. 5-1). When the power supply was turned off and the electrodes short-circuited, a current passed due to the difference in the potentials of the two electrodes. This current was in the opposite direction to that when the power was on. The measured voltage during the off time was between 1.8 and 2.3 V. This value is of the same order of magnitude as the values in Fig. 5-1. For example, after 2 hours of dewatering under a constant current of 90 mA, the pH was 1.2 near the upper electrode (anode) and 10.0 near the lower electrode (cathode) for a 2.0 cm initial bed height and a Bentonite suspension of initial salt and solid concentrations of 10^{-2} M $CaCl_2$ and 9.1 wt%, respectively. The measured emf when the power was interrupted was 2.3 V. Point (a) in Fig. 5-1 represents the condition at an anode covered with PtO_x at pH = 1.2. Point (b) in Fig. 5-1 represents the condition at a cathode which is pure platinum at pH = 10. There is a difference in the potential between these two points of about 2.4 V, which is in rough agreement with the measured values (1.8-2.3 V).

5.2 Interrupted EOD

The variation of the current during interrupted EOD under various conditions was presented in Ch. 4. The rapid decrease in the current during on-time or increase during off-time were related to the polarization phenomenon. The polarization of an electrode is commonly classified as follows: ohmic polarization, concentration polarization, activation polarization, crystallization polarization and reaction (or chemical) polarization. Concentration and reaction polarization result from a difference between the activity (or state) of the reactants or products of the electrode processes at the electrode itself with the corresponding value in the bulk phases (Hampel, 1964). The rate of reaction at the electrodes is usually limited by the rate of mass transfer; so a concentration gradient exists. For example, reaction at the electrode can be the electrochemical deposition of the H^+ ions, Eq. (5-4), which might be formed from dissociation of a weak acid or a water molecule. Low mass transfer rates or the rates of dissociation of a weak acid or water may limit the supply of hydrogen ions This results in a drop in the current (when the voltage is held constant or a shift in the voltage when the current is held constant) during on-time During the off-time the concentration of H^+ becomes more uniform so that for the subsequent on-time the same variation of current occurs. In addition, during the off-time another set of reactions occurs on the electrodes, like Eqs. (5-1) to (5-3), producing an electrochemical cell and a current in the reverse direction, i.e. from lower to upper electrode Similar to the on-time situation, a concentration gradient of the concerned spices exists near the electrodes thus resulting in a drop in the absolute value of current (see section 4.2).

The IS process with the shortest off-time (0.5 s) increased the final average solid content compared to the DC process under various conditions and with different materials, namely Bentonite, kaolin and red clay. Figure 5-2 shows the difference between the volume of water removed by IS, Q(IS), and the volume of water removed by DC, Q(DC), as a function of the energy supplied to the electrodes. Data are shown for off-times of 0.5, 3 and 20 s. As the off-time decreased the volume of water removed increased. Figure 5-3 shows similar data for IS (30/0.5) with different electrolyte concentrations and Bentonite concentrations. In all cases IS (30/0.5) removed about 20-40% more water than DC. Figure 5-4 compares an IS (30/0.5) run with a run in which DC was followed by a period of IS (30/0.5) applied after dewatering had stopped Nearly 2 cm^3 of additional water were removed with an energy expenditure of about 250 J. This represents an average energy of dewatering of about 2.5 kJ/mole, a value about 5% of the heat of vaporization and

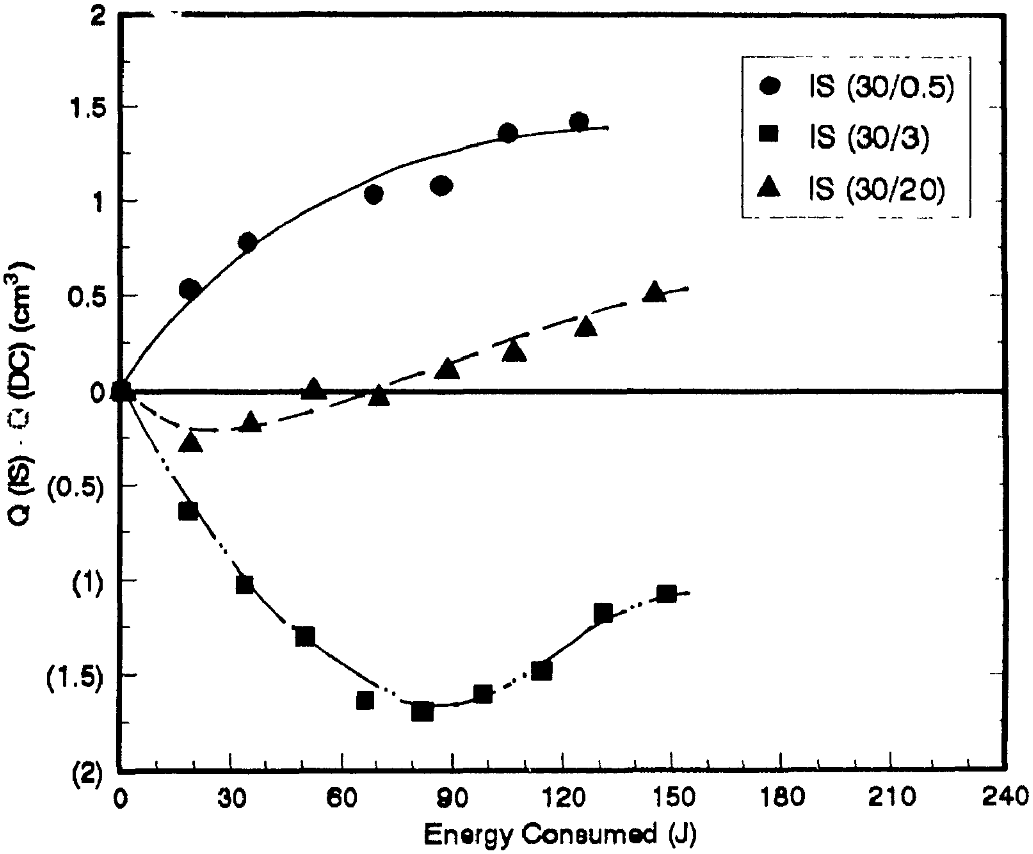


Figure 5-2 Difference in the volume of water removed between IS and DC for various off-times vs. energy consumed for Bentonite. (9.1 wt%; 0 M; 1.0 cm; 2.75 V)

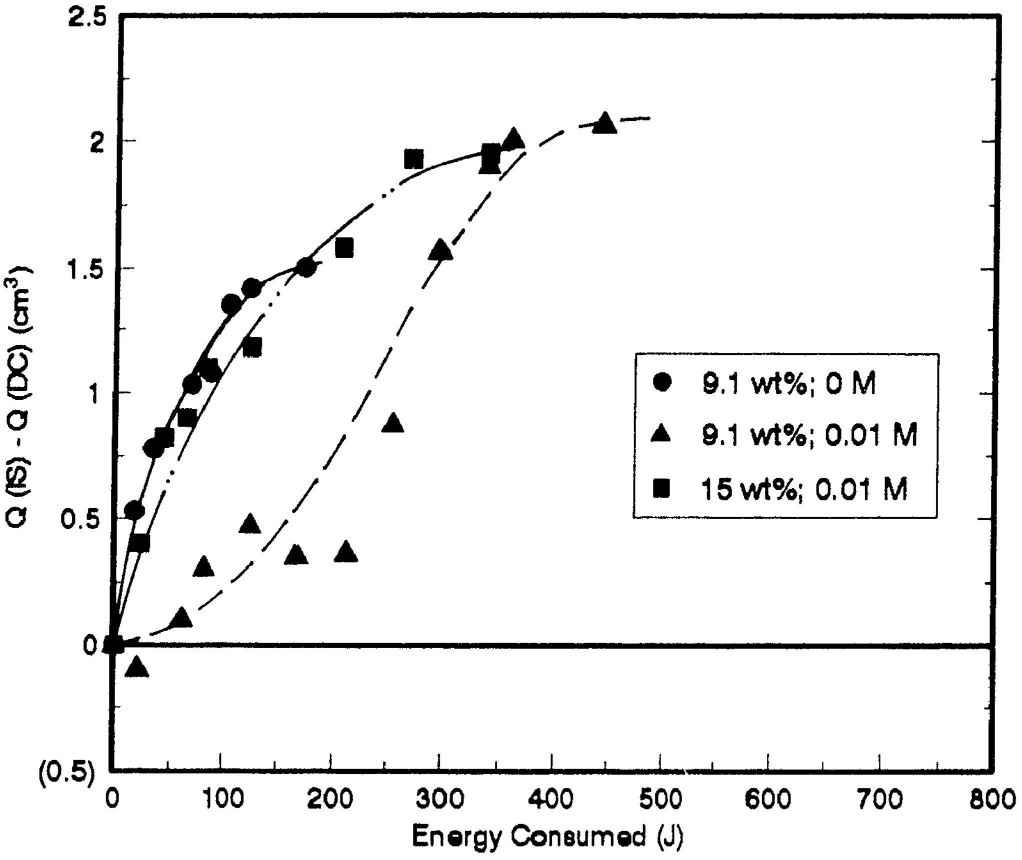


Figure 5-3 Difference in the volume of water removed between IS (30/0.5) and DC vs. energy consumed for Bentonite. (1.0 cm; 2.75 V)

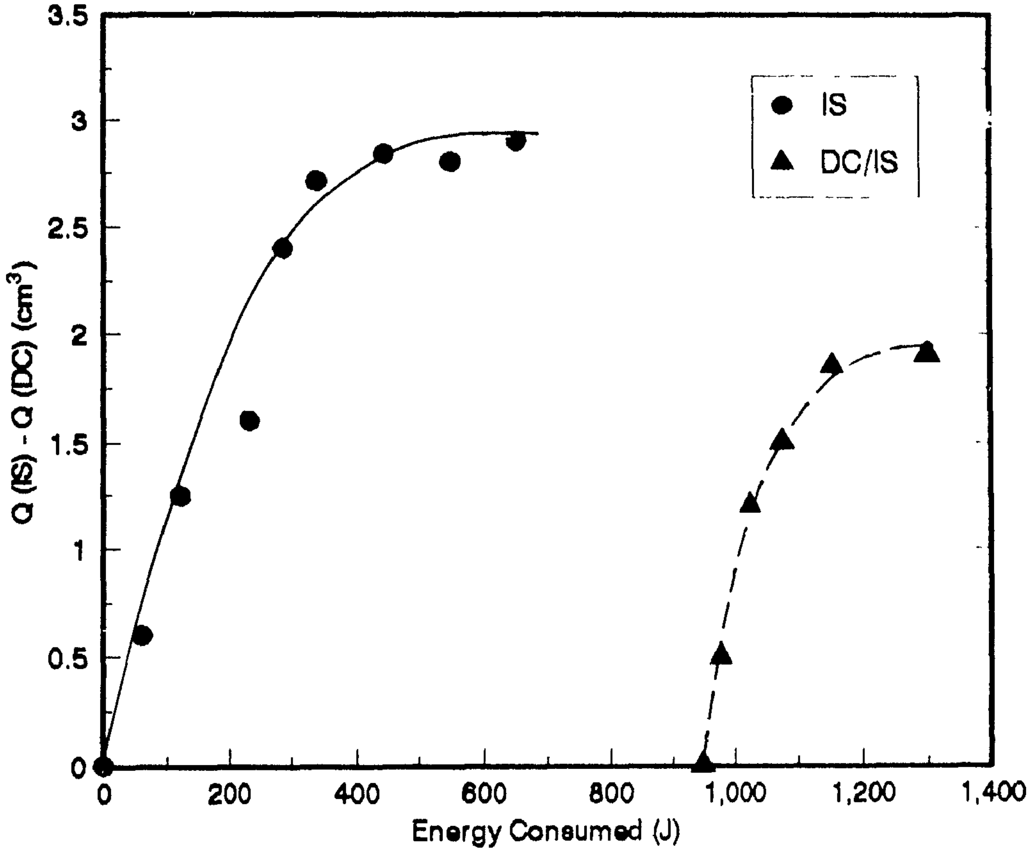


Figure 5-4 Difference in the volume of water removed between IS (30/0.5) and DC vs. energy consumed for Bentonite. (9.1 wt%; 0.01 M; 1.5 cm; 30 mA)

comparable to that obtained early in a DC dewatering run. This is a clear indication of the effectiveness of IS (30/0.5).

5.3 Effect of Initial Bed Height

Figure 5-5 shows the final percentage of water removed as a function of the initial bed height for DC dewatering with a constant current of 90 mA. Two sets of experiments with two initial salt concentrations are presented; 0 M and 10^{-2} M $CaCl_2$. For comparison, the data of Ju (1990) are included for a 9.1 wt% Bentonite suspension dewatered under constant DC voltage with the same initial applied field for each height. Ju found that the driest bed was obtained for an initial bed height of 2.1 cm. In the present work for the 0 M case, a bed of 1.0 cm initial height was the driest at the end of dewatering and for the 10^{-2} M case, all beds had nearly the same final water content.

For 0 M initial salt concentration and the largest height, 2.0 cm, the upper part of the bed became dry and large cracks appeared. Ju reported the same observation for 2.8 cm initial bed height. The electrical resistance of the bed also increased, possibly because of the poor contact at the electrodes due to the large volumes of gas liberated. The largest amount of water was removed at an intermediate bed height; 1.0 cm in this work and 2.1 cm in Ju's work. For heights up to the intermediate ones the final percent removal increased with height. Ju hypothesized that this was the result of an increased field strength in the middle portion of the bed (Ju, 1990).

For runs with 10^{-2} M initial salt concentration, all beds had nearly the same final water content. Figure 4-7 shows that the water flux per unit charge was

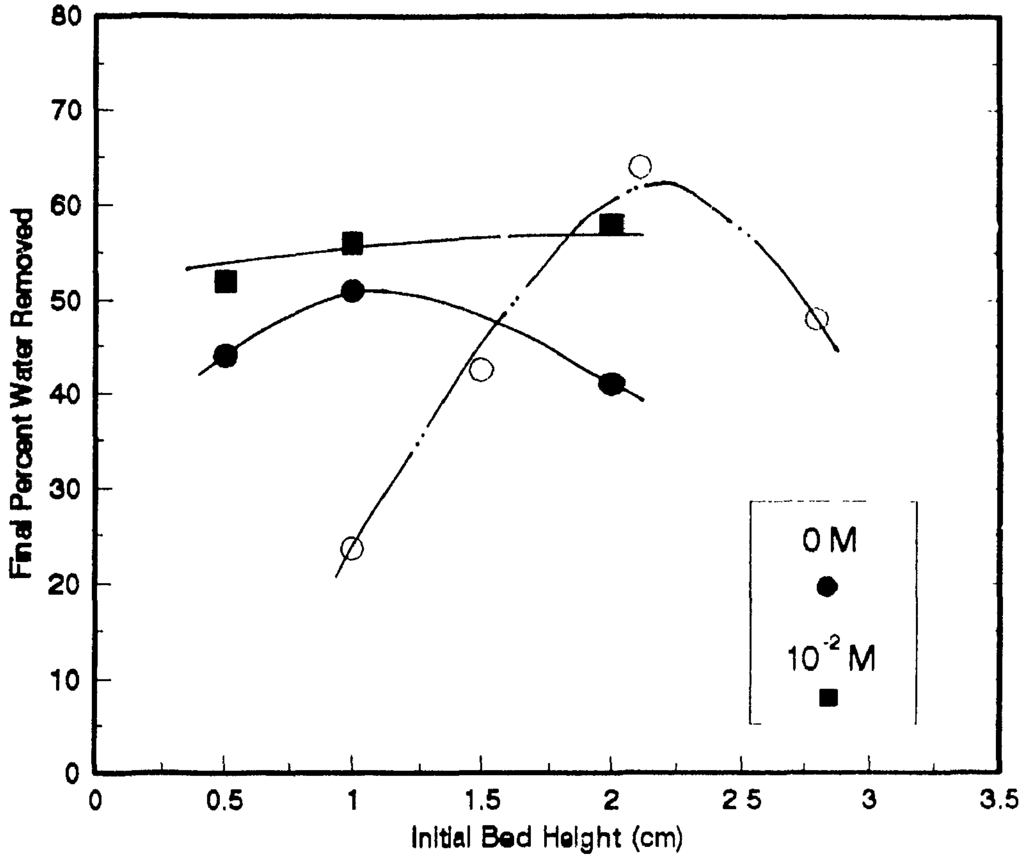


Figure 5-5 Final percentage of water removed vs. initial bed height for Bentonite Filled symbols for present data (9.1 wt%; 90 mA). Open symbols for Ju (1990), (9.1 wt%; 0.001 M; E_0 = 2.8 V/cm)

independent of the bed height. The volume of water removed as a function of energy consumption is presented in Fig. 5-6. The volumes of water removed were the same for all initial bed heights until near the end of dewatering when an unsaturated layer was formed in the upper part of the bed thus preventing further dewatering (Yoshida et al, 1985). These results are in agreement with the implications of the Helmholtz/Smoluchowski theory in that the flux per unit charge is independent of the bed height (see section 5.4). The effects of the unsaturated layer and the gas liberation at the electrodes are more important when no electrolyte is used (0 M case), since they resulted in different final water content (see Fig. 5-5). Previous workers found that the water removal rate and the final solid content increased with the addition of electrolytes (Lockhart, 1983; Ju, 1990). Figures 4-1, 4-5 and 5-5 show similar results. These figures also show that the increase is greater for a thicker bed.

The reverse current and potential, which were discussed in sections 5.1 and 5.2, and the ohmic resistance near the electrodes reduced the effective field strength and current in the constant DC voltage experiments. Ju (1990) reported lower current for the thinner beds although the initial field was the same. When the applied voltage was lower than the reverse potential, no current flowed. Yoshida (1992) reported that there was no current up to a threshold voltage when a uniform bed was used.

Since the current was lower for thinner beds (in constant voltage experiments with the same initial field), the water flux per unit charge was higher (Ju, 1990). In constant current experiments, since higher voltage must be applied to keep the current constant, due to the reverse potential and ohmic voltage drop, the water flux per unit charge was lower for thinner beds (see Fig. 3-4). When a sufficiently high current or voltage was applied under suitable bed conditions no effect of initial

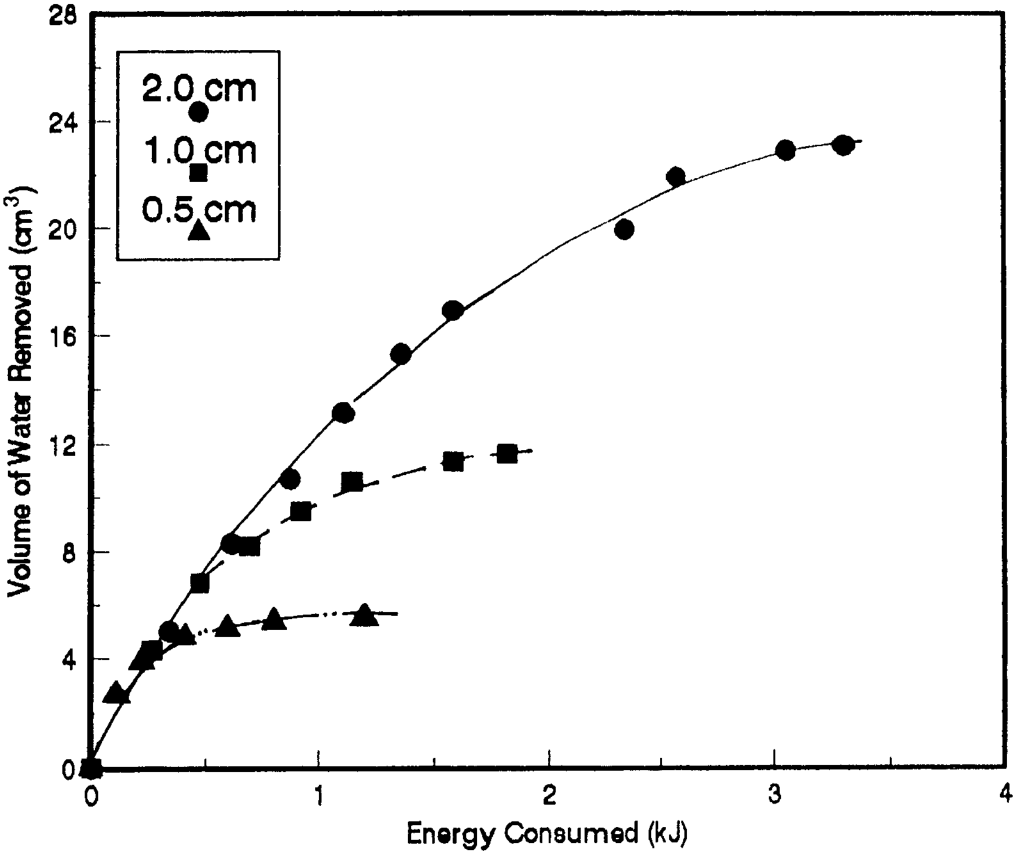


Figure 5-6 Volume of water removed vs. energy consumption for Bentonite under constant current. (9.1 wt%; 0.01 M; 90 mA)

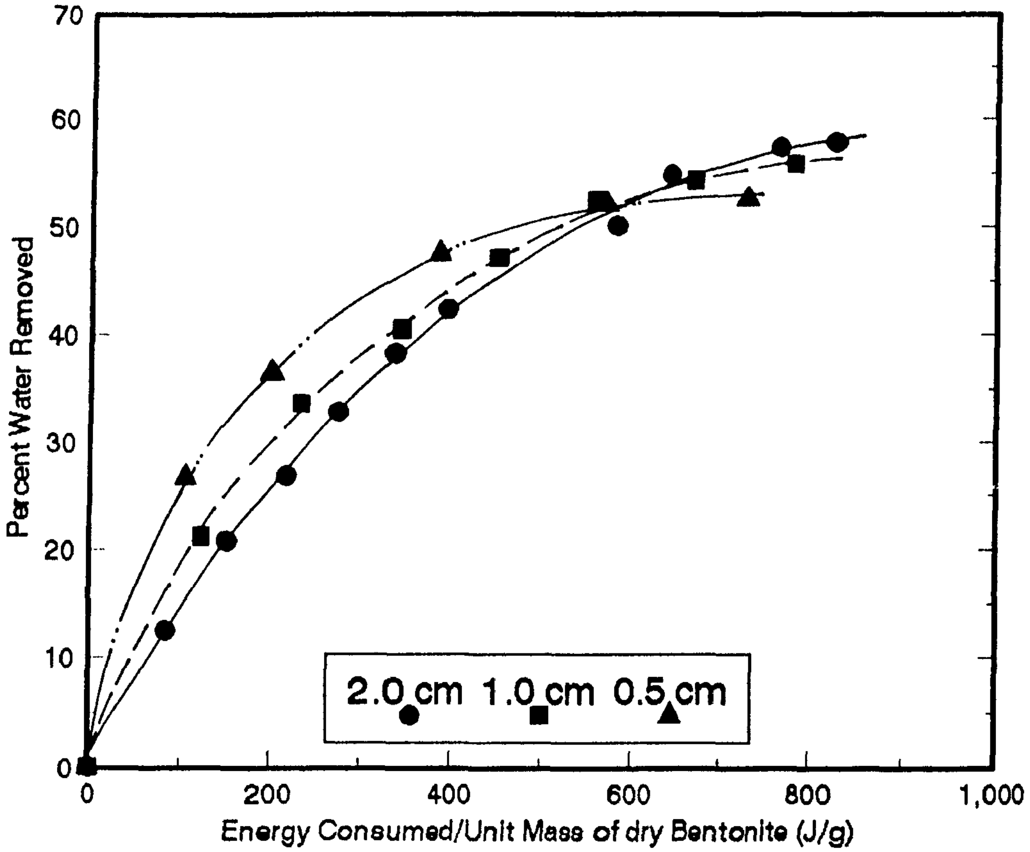


Figure 5-7 Percent water removed vs. energy consumed per unit mass of dry Bentonite under constant current for three bed heights. (9.1 wt%; 0.01 M; 90 mA)

height on the water flux was found (see Fig. 3-15).

In Figure 5-7 the percent of water removed is plotted as a function of the energy consumption per unit mass of dry Bentonite for the 10^{-2} M initial salt concentration case. It shows that the thinner the bed, the lower the energy consumed per unit mass of dry Bentonite to remove the same percent of water, i.e to get the same final average solids content. The unsaturated layer formed similarly in all beds, since the rates of water removal were the same. Similar unsaturated layers affect more a thin bed than a thick bed (the big voltage drop over an unsaturated layer depends to the percentage of its resistance respect to the total resistance of the bed). Near the end of dewatering, where unsaturated layer was formed, the thin beds loosed their advantage (see Fig. 5-7)

5.4 Comparison with Helmholtz/Smoluchowski Theory

Equation (1-6) can be rewritten as:

$$\frac{u_e A}{i} = \frac{-\zeta \, \varepsilon \, \epsilon_0}{\eta \, \lambda} \tag{5-5}$$

The quantity $u_e A / i$ represents the volume of water transported in m^3 per coulomb of charge. The water flux per unit charge, W, is given by

$$W = 5.344\times10^9 \left(\frac{u_e A}{i}\right) \quad \frac{mole}{Faraday} \tag{5-6}$$

where the factor 5.344×10^9 has units of $mole{\cdot}C / m^3{\cdot}Faraday$. The energy of dewatering, e_d is given by

$$e_d = 1.806\times10^{-8}\left(\frac{V_0\, i}{u_e A}\right) \quad \frac{kJ}{mole} \tag{5-7}$$

where the factor 1.806×10^{-8} has the units of $m^3{\cdot}kJ\,/\,mole{\cdot}J$. Equations (5-5) and (5-6) indicate that the water flux per unit charge is independent of bed height and solid content. Since the addition of electrolytes decreases the magnitude of the zeta potential, ζ, and increases the conductance, λ, the water flux per unit charge should decrease with electrolyte concentration. In the interrupted process, since no current is applied during the off-time, eq. (1-6) indicates that no dewatering should occur thus the rate of dewatering should decrease in the same ratio as the fraction of off-time. Since the rate of dewatering and the mean current (in interrupted voltage runs or the mean voltage in interrupted current runs) decrease in the same ratio, the water flux per unit charge and the energy of dewatering should not change (see eqs. 5-6 and 5-7). Further, no effect of relative motion between the electrodes is expected from eqs. (1-6), (5-6) and (5-7).

The results which were discussed in the previous sections did not agree with the Helmholtz/Smoluchowski theory for the effects of interruption and electrolyte concentration. IS (30/0.5) gave greater dewatering than DC with a lower energy consumption. Higher $CaCl_2$ concentration increased the rate of water removal as well as the final solid content. Table 5-1 compares measured values of W and e_d at the start of electroosmotic dewatering with values calculated from eqs. (5-6) and (5-7). The first entry in the table is for a constant voltage run in which the conductance of the collected water was measured. The second entry is from Ju (1990) who used the same Bentonite as in this work. The third entry is for a different Bentonite which has a much higher zeta potential. The agreement between the data and the predictions of the Helmholtz/Smoluchowski theory is poor in all cases. For the present results the value of W computed from eq. (5-6) is roughly one-half of the experimental value while the value of e_d computed from eq. (5-7) is roughly a factor of two larger than the data. The agreement with the data of Yukawa (1978) is even worse. The predicted values of W and e_d differ by an order of magnitude from the experimental values with the predicted W being larger than the data and the predicted e_d, smaller.

Table 5-1 Comparison of data with Eqs. (5-6) and (5-7)

Source	ζ (mV)	λ (S/m)	V_0 (V)	W(moles/Faraday)		e_d(kJ/mole)	
				Eq.(5-6)	Data	Eq.(5-7)	Data
This work*	-15	0.238	5.5	269	570	1.97	0.8
Ju (1990)*	-15	0.292	2.8	219	480	1.23	0.4
Yukawa** (1978)	-66	0.142	5.0	1985	230	0.24	2.5

* 9.1 wt%; 0.01 M; 2.0 cm, ** 20 wt%; 0 M; 2.7 cm

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

From experiments on electroosmotic dewatering of Bentonite, kaolin and red clay under continuous and interrupted voltage or current the following conclusions are drawn:

1. Electroosmotic dewatering can remove significant amounts of water (up to 70% of the initial water was removed) with energy expenditures well below the energy required to vaporize the water.

2. Periodic interruption of the power for a short time when the electrodes were short-circuited, IS (30/0.5), removed more water with the same energy consumption as DC. As well, nearly the same amount of water was removed when IS (30/0.5) was applied at the end of a DC run as was obtained with IS (30/0.5) applied from the start dewatering.

3. The height at which the maximum percentage of water was removed, was different for different condition of voltage and current. Because the reverse potential, resistance near the electrodes and polarization cause this shift in optimum height.

4. A thin bed (0.5 cm) was dewatered to the same average percent solids using less energy than thicker beds.

5. Rotation of the upper electrode had no significant effect on dewatering.

6. The water removal rate and the final solid content increased with the addition of $CaCl_2$.

7. The Helmholtz/Smoluchowski theory did not agree with the experimental results for the effects of interruption in power and electrolyte concentration.

6.2 Recommendations

The following areas are recommended for further experimental research:

1. A study to show the effect of the frequency in the interrupted regimes (IS and IO).

2. A study of the effect of reversing the polarity of the electrodes. This interrupted regime may result in a more uniform water content, pH and electrochemical changes, thus preventing excessive drying at the anode and reducing the reverse potential.

NOMENCLATURE

A	cross sectional area of the bed	[m^2]
a	cross sectional area of a capillary	[m^2]
C_0	initial $CaCl_2$ concentration	[M]
D_0	smallest diameter in size distribution	[m]
D_m	largest diameter in size distribution	[m]
E	electric field strength	[V/cm]
E_a	applied field strength	[V/cm]
E_{ox}	oxidation potential	[V]
E_T	energy consumption	[J]
E_0	initial field strength	[V/m]
e_d	energy of dewatering	[kJ/mole]
F	Faraday (96500 Coulombs)	
H	bed height	[cm]
H_0	initial bed height	[cm]
i	electric current	[mA]
K^{1}	Debye thickness	[m]
M	molecular weight of water	[g/mole]
$n(D)$	number distribution	
Q	volume of water removed by electroosmosis	[cm^3]
$\dot{Q}$	rate of water removal	[cm^3/s]
R	capillary radius	[m]
S_0	initial solid content	[wt%]
t	time	[s]
t_1	on-time	[s]
t_2	off-time	[s]
u_e	electroosmotic velocity	[m/s]
V	overall voltage	[volt]
V_0	initial applied voltage	[volt]

W	water flux per unit charge	[moles/Faraday]
ζ	zeta potential	[volt]
ε	dielectric constant of the bulk fluid	
ϵ_0	permittivity of free space	$[c^2/J.m]$
ϵ_w	volume fraction of water	
η	viscosity of bulk fluid	[kJ/m.s]
λ	specific conductance of the bulk fluid	[S/m]
ρ	density of water	$[kg/m^3]$
Ω	rotation speed	[rpm]

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