Electrokinetic dewatering of a phosphate clay

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Abstract

The principles of electrokinetic dewatering are: (1) electrophoresis, the movement of colloidal particles in a direct current electric field; (2) dielectrophoresis, the movement of colloidal particles in a non-uniform electric field; and (3) electro-osmosis, the water flow in porous media in a direct current electric field. Electrokinetic dewatering of a phosphate clay was investigated in an experimental program. The results show that the velocity of sedimentation is controlled by the applied current density and that electro-osmotic permeability dominates the effectiveness of electrokinetic consolidation. The intermittent current and polarity reversal can significantly improve the effectiveness of electrokinetic dewatering and reduce energy consumption and adverse electrode reactions. © 1997 Elsevier Science B.V.

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1. Introduction

The US Bureau of Mines pioneered the research and development of electrokinetic dewatering of tailings from mineral processing and coal preparation in the 1960s (Stanczyk and Feld, 1964; Sprute and Kelsh, 1975a; Sprute and Kelsh, 1975b; Sprute and Kelsh, 1980; Sprute and Kelsh, 1982). Several successful field applications were reported including, for example, a full scale field test that was performed on a metallic tailing in the Idaho State Mining District (Sprute and Kelsh, 1975b). An underground stope approximately 3.5 feet wide and 160 feet long was backfilled with a 3 feet deep tailing from a metallic mine. Perforated iron pipes, 2 inches in diameter, were laid on the bottom of the stope as the cathode and an iron mesh was placed on the top as the anode. Water was driven to the bottom and drained through the cathode and sand-filled trench.

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After application of a DC voltage for approximately 2.5 h the filling was dewatered and hardened dramatically so that walking on the surface was easily accomplished. After 29 h, the surface hardness measured by a concrete penetrometer increased from zero to 264 psi. The applied voltage in the process ranged from 300 to 450 V, with the corresponding electric current ranging from 10 to 63 A. The power consumption was estimated at 13 kWh per cubic meter of tailing which, with proper technical improvement such as eliminating the power loss along the stope walls could have been reduced.

The CSIRO of Australia began research on electrokinetic dewatering of tailings in the late 1970s (Lockhart, 1986). More than 60 tailings from coal preparation plants, sand washing plants, mineral processing and water purification plants were tested. Significant dewatering, consolidation and hardening effects were achieved in a variety of mine wastes. For example, a successful field test using electrokinetic dewatering was conducted in 1985 for an existing sand washery pond (Lockhart, 1986). In accordance with normal practice at the washery, the pond was filled from one corner with the dilute tailings stream and clear water overflowed through a pipe in the opposite corner until the mudline level of tailings reached the bottom of the overflow pipe. Rows of anodes and cathode-drains were then placed 4 m apart. After 2 months of treatment, between 4000 and 4500 tonnes of tailings 95% below 20 μm in size, were dewatered to about 70% solids. The power consumption was estimated as 0.7 kWh per tonne on a dry solid basis. Without electrokinetic treatment, the dewatering and consolidation would have taken several years.

In spite of several successful field applications of electrokinetic dewatering of mine tailings, the technique is not commonly used in practice. The reasons may be primarily attributed to limited understanding of the principles of electrokinetics which has resulted in (1) high power consumption in some cases; (2) non-effectiveness caused by using the technique indiscriminately not knowing that electrokinetics may be very effective on certain materials and not effective at all on others; and (3) improperly designed operating systems.

In this paper, the principles of electrokinetic dewatering are discussed, followed by an experimental investigation of a phosphate clay suspension from a waste disposal pond in Florida to investigate the factors influencing the effectiveness of electrokinetic dewatering.

2. Fundamentals of electrokinetic dewatering

The application of an external electric field induces the relative movement of solid particles and water in a suspension. The principles involved in the process are derived from three different origins, namely, electrophoresis, dielectrophoresis and electro-osmosis. *Electrophoresis* is the motion of electrically charged particles under the influence of an external DC field. The charged particles move towards the anode if they are negatively charged or to the cathode if they are positively charged. *Dielectrophoresis* is the motion of particles caused by polarization effects in non-uniform electric fields (Pohl, 1978). The theory of dielectrophoresis in clay–water–electrolyte systems was developed recently (Shang et al., 1994). Particles with surrounding diffuse double layers

may be considered as equivalent dipoles controlled by charges in the double layer. When an external electric field is imposed, the charges in the diffuse double layer are polarized. If the electric field is non-uniform, the dielectrophoretic force is generated by the polarization effect. It is possible to recognize the dielectrophoretic force as (1) it can take place in either AC or DC fields, and (2) it acts in a shorter range and is several orders of magnitude lower than the electrokinetic force. The total electrokinetic force on a particle in an external electric field is the vectorial summation of electrophoresis and dielectrophoresis. Because of the action of the electrokinetic forces, the particles form a condensed structure. When a soil is formed, i.e., the system can be modelled as a "water-in-solid" system consisting of a porous solid skeleton filled with mobile water, *electro-osmosis*, the water flow induced by a direct current (DC) electric field through porous media, plays the dominant role. Electro-osmosis has been applied to various aspects in soft soil engineering, such as dewatering, stabilization and consolidation of soft silty clays in excavations and in construction of foundations, embankments and dams since the first successful field application by Casagrande, 1948.

An electrokinetic dewatering process of fine-grained materials can be identified as:

(A) Sedimentation. Suspended particles settle at the resultant velocity of the electrokinetic forces and the gravitational and electrochemical forces.

(B) Consolidation. Once a porous soil is formed it is further consolidated primarily by electro-osmosis.

The influencing factors of electrokinetic processes arise from both internal and external sources. The internal or intrinsic factors are the physical and chemical properties of materials, including:

(A) Grain size and mineral type. Electrokinetics works more efficiently in fine-grained materials where the surface properties of particles are dominant. Typically, electrokinetics becomes predominant in systems where 30% or more of the particles are finer than 2 μm. Experiments also indicate that among different clay types electrokinetics is more effective in silty clays of moderate plasticity (e.g. kaolinite and illite) than in high plastic clays containing swelling clay minerals (e.g. smectites) (Lockhart, 1983b).

(B) Salinity. In materials with high salt concentrations, electrokinetics is not effective (Lockhart, 1983a). On the other hand, a moderate salt concentration would allow a better dewatering effect at a lower voltage and therefore reduce power consumption.

(C) pH. Since the electrical charges on colloidal particles vary with pH of the solution, the effectiveness of electrokinetics changes accordingly. It has been reported that electrokinetics was not effective in a low pH environment (pH < ~ 6) (Lockhart, 1983a) but was very effective in a high pH environment (pH > 9) at even fairly high salinity (Lo and Shang, 1995).

(D) Hydraulic permeability. The hydraulic permeability plays a critical role in electro-osmotic consolidation. The relative importance of hydraulic flow and electrokinetic flow depends on the relative magnitude of the electrokinetic permeability k_e and hydraulic permeability k_h of the material (Mitchell, 1993).

The external factors governing electrokinetics are the parameters of the operation system, including:

(E) Current density. The effective current density in an electrokinetic dewatering process varies with the material properties. Determining the effective current density and

applying it judiciously throughout the entire treatment zone are crucial to the success of an electrokinetic treatment. The magnitude and spatial distribution of the current density are determined by the applied voltage and spacing of electrodes which are the primary design consideration of the operation system.

(F) Electrode material and design. Materials used for the fabrication of electrodes influence their performance, including efficiency, corrosion and lifespan. Excluding expensive materials such as silver and platinum, iron and copper are more effective than aluminum, lead and carbon black in field applications, as observed in experiments (Sprute and Kelsh, 1980; Lockhart, 1983b). Iron or steel electrodes have the advantage of low cost whereas copper or brass electrodes are more efficient on current conduction. The design of the electrodes includes the geometry, perforation and insulation (if appropriate), and should minimize electric losses which reduce efficiency or even stop the processes completely.

(G) Electrode layout. Horizontal electrode configurations are preferred for new disposal ponds. The electrodes may be composed of metallic meshes or pipes, placed horizontally with appropriate vertical spacing. For existing tailing ponds, installation of horizontal electrodes may not be technically or economically feasible. The vertical electrode configurations may be used in these cases. The electrodes, made of perforated metallic pipes or screen wire poles wrapped with filter cloth to prevent entry of solids, are inserted vertically into the slurry at design values of spacing and depth.

In the early investigations on electrokinetic dewatering of mine tailings, some researchers applied intermittent current (a pulse current at pre-determined on/off intervals) to improve effectiveness and to reduce power consumption (Sprute and Kelsh, 1974; Sprute and Kelsh, 1975a; Sprute and Kelsh, 1980; Baglin and Macintosh, 1987). However, some researchers thought that the observed effects might be attributed to the efficiency of the drainage system, not the intermittent current (Lockhart, 1986). Furthermore, previous work (Lo et al., 1991a; Lo et al., 1991b; Gray and Somogyi, 1977; Chappell and Burton, 1975) suggested that the reversal of polarity or the direction of the applied voltage during an electrokinetic process could improve dewatering and neutralize electrode reactions. However, detailed study of the mechanism involved, especially the chemical analysis during the process, has not been reported.

3. Experimental study

Phosphatic clays are the primary waste disposal problem of the Florida mining industry. The phosphatic clays, separated during the beneficiation of the phosphate matrix, are stored in large, diked ponds to be dewatered. These clay suspensions have very low solid contents (3% to 6% solids) and are composed of colloidal particles which settle very slowly and may require decades to consolidate to the range of 20–25% solid. The dewatering techniques under investigation include loading and squeezing by mechanical devices such as centrifuges, and chemical treatment using flocculants and coagulants, which are all considered very capital intensive (McLendon et al., 1983).

3.1. Previous investigation

An investigation of electrical dewatering of the phosphate clays was conducted by the US Bureau of Mines in 1964 (Stanczyk and Feld, 1964). The phosphate slime was recovered from Bartow, FL, with typically 90% of the particles finer than 1 μm. The solid content of the slime was 14% to 17%. Upon application of a DC electric current, the solid contents of the slime were increased to the range of 25% to 39% in various treatment periods (1 to 27.5 days) and sample sizes (50 to 8000 pounds). The large scale laboratory test using an 8000 pound slime sample was analyzed prior to the experimental program. The slime was deposited in a cylindrical container, 6 ft in diameter and 4 ft in depth. The cathode, made of 1 ft diameter steel screen wire covered with cheesecloth, was vertically installed at the centre of the container. Eight anodes made of 11/4 inch steel rods were installed surrounding the cathode at a radius of 2.5 ft. The depth of slime in the container was 3.5 ft. A DC voltage of 13 to 15 V was applied for a period of 27.5 days. The current density under the specific electrode configuration was non-uniform, ranging from 10.8 A m^{-2} at the centre of the container (cathode) to 2.1 A m^{-2} at the circumference of the container (anode). By the end of the treatment period, the solid content of the slime was 25.3%, an increase of 49% from the initial 17% at an average power consumption of 21.3 kWh per ton of water recovered. It was concluded that the rate of water removal was considered too slow to be commercially feasible.

3.2. Material properties

The phosphate clay used in the experimental study was collected from a phosphate clay tailing pond in Florida. Table 1 summarizes the properties of the clay.

3.3. Apparatus and procedure

The experiments were conducted in an electrokinetic cell and a model tank. The electrokinetic cell was 9 cm in diameter with 20 cm high plexiglas tubing as shown in Fig. 1a. Drainage can be controlled at the bottom of the cell. Two voltage measurement ports were installed 10 cm apart on the wall to monitor the electrical potential gradient. The parallel plate electrodes were 9 cm in diameter with 0.2 cm thick steel mesh. A control switch was used for application of intermittent current at programmed intervals. Four tests (FPC-1, 2, 3 and 4) were performed in the electrokinetic cell using the following procedure. (i) Sedimentation by gravity. The sample was drained through the bottom drainage channel for 24 h before treatment. Top water was decanted periodically and the cells were filled to the top again with the clay suspension after decanting. At the end of this period the hydraulic flow through the bottom drain was less than 1 mL per 48 h and the rate of sedimentation was less than 1 mm per 48 h. The gravimetric solid content of the suspension was measured at the end of this stage. (ii) Electrokinetic sedimentation. A regulated voltage was applied using the configuration of top-cathode and bottom-anode. The current density and intermittence were the variables during the tests. The sedimentation and volume change were measured through the changes of mudline. A test was terminated after obtaining two identical mudline readings over two

Table 1
Summary of soil properties

Solid composition	
Sand	2%
Silt	30%
Clay	68%
LL	141%
PL	43%
Kaolinite	45–55%
Smectites	20–30%
Illite	10–15%
Quartz	7–10%
Feldspar	< 5%
Carbonates	< 3%
CEC	33.1 meq per 100 g
Specific surface	217 m^2 g^{-1}
Conductivity, clay	4.5 mS m^{-1}
Water composition	
Conductivity, water	36.7 mS m^{-1}
pH	6.9
Na	27.5 mg L^{-1}
K	2.25 mg L^{-1}
Ca	42.5 mg L^{-1}
Mg	17 mg L^{-1}
SO$_4$	80 mg L^{-1}
Cl	18 mg L^{-1}
Orthophosphate	< 4 mg L^{-1}

hours. After treatment, the solid content of the clay was measured at 3 locations at various depths and an average was taken.

A model tank was used to investigate (1) sedimentation in a non-uniform electric field; (2) downward water flow induced by electro-osmosis; (3) effect of polarity reversal; and (4) chemical changes of water collected during the electrokinetic dewatering process. As shown in Fig. 1b, the tank was made of plexiglas plate, 286 mm long, 119 mm wide and 254 mm deep. A lid with a rubber seal was placed on top of the tank during testing to reduce the drying effect. Drainage can be controlled via two drainage valves at the bottom of the tank. Two copper rod electrodes of 1 mm diameter and 100 mm apart were installed at the bottom and connected to one another. A steel mesh of 1 mm thick, 200 mm long, 115 mm wide and 5 mm nominal opening was used as the top electrode, as shown in Fig. 1b. The mesh was placed with the left edge in contact with the tank wall to examine the effect of asymmetry of the electric field. After the pretreatment which was identical to that in the cell tests, electrokinetic dewatering was undertaken over a period of 67 h divided into two stages, i.e., Stage 1: 31 h sedimentation using top-cathode and bottom-anode, and Stage 2: 36 h electro-osmotic consolidation using top-anode and bottom-cathode. The mudline was recorded from six locations during Stage 1. When the mudline remained constant over two hours, the polarity of the voltage was reversed for consolidation treatment and water expelled via two bottom drainage channels was recorded separately until no water was collected
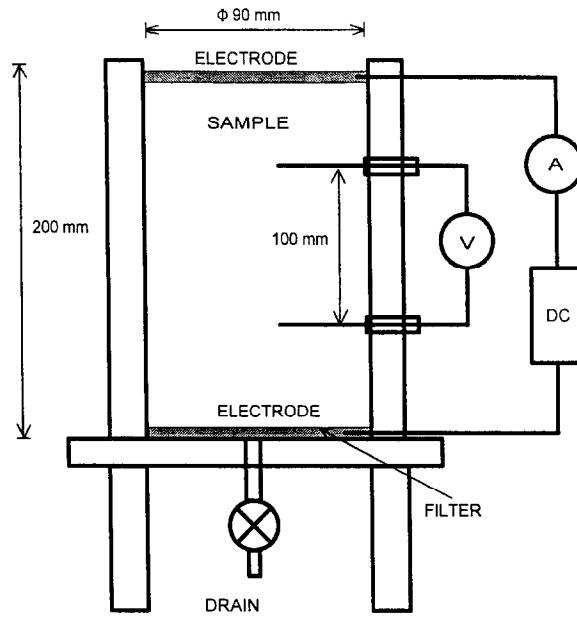
(a) Electrokinetic Cell
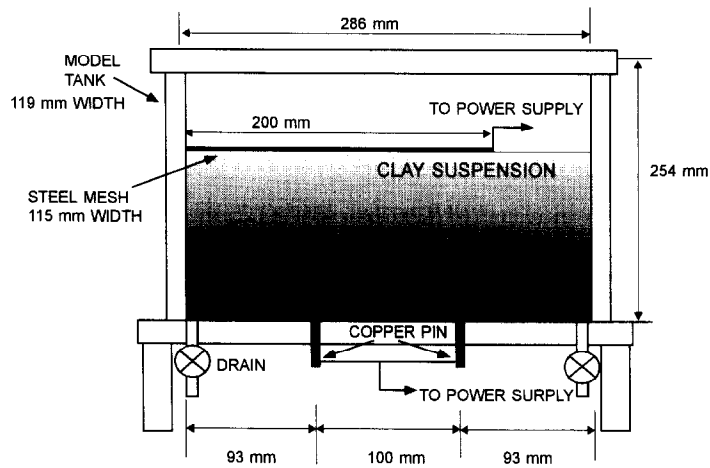
(b) Model Tank

Fig. 1. Experiment apparatus: (a) electrokinetic cell; (b) model tank.

during a 2 h period. Water samples were collected periodically from the top of the tank during sedimentation and from the drainage channels during consolidation for chemical analysis.

3.4. Results of cell tests

A summary of the test conditions and results is included in Table 2. At the end of gravitational sedimentation, the solid contents of the clay suspensions ranged from 13.2% to 19.5%. After 24 h of treatment, the solid contents were in the range of 25%–34%, representing increases from 67% to 94%. The applied voltages were limited to ~ 100 V m^{-1} or below for practical applications. Intermittence current was applied in some of the tests with power ON and OFF intervals specified in Table 2. The voltage was applied in descendent increments in tests FPC-1 and FPC-2, ascendent increments in test FPC-3 and was constant in test FPC-4. Sedimentation was observed immediately after the power was turned on and the occasional drops of water through the bottom drainage channel completely stopped. At the edge of the top electrode plate a gap formed in less than 2 h as shown in the photograph on Fig. 2 indicating clay particles were expelled toward the less intensive field; this could be attributed to dielectrophoresis.

Figs. 3–6 present the sedimentation (in mm), volume change (in percentage) and current density during treatment in the cell tests. After 24 h, the volume changes of all samples ranged from 30% to 40%. It appears that sedimentation slowed down eventually with time and stopped after about 15 h of voltage application. The sedimentation velocity (mm h^{-1}) is defined as the initial slope of the sedimentation curve at the moment of voltage variation and is plotted against current density in Fig. 7. A linear trend is clearly defined, suggesting the sedimentation of the clay suspensions is proportional to the current density. Fig. 7 also shows that there appeared to be a threshold current density at $j \approx 1$ A m^{-2}, below which electrokinetic dewatering was

Table 2
Summary of electrokinetic cell tests; treatment time is 24 h

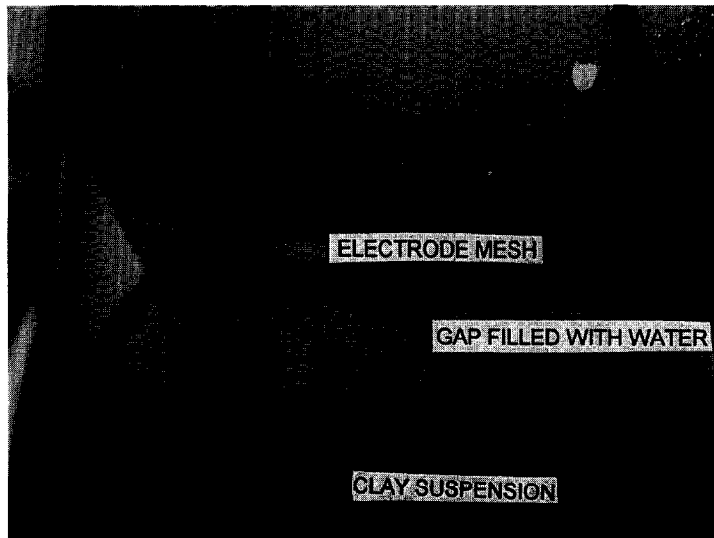| Test No.		FPC-1	FPC-2	FPC-3	FPC-4
Solid content					
Initial	%	13.2	19.5	15.7	15
Final	%	25.7	33.5	26.3	26.5
Increase	%	94.4	72	67.5	76.7
Sample height					
Initial	mm	184	193	200	192
Final	mm	111	127	139	125
Decrease	%	− 39.7	− 34.2	− 34.9	− 34.9
β		1	0.94	0.88	0.75
ON/(ON + OFF)	min min^{-1}	on	15/16	15/17	15/20
Applied voltage		16	20	3	15
		10	19.5	6	
U_0	V			17	
				8	

Fig. 2. Photograph showing gap between soil and top electrode mesh.

ineffective. The phenomenon can be interpreted from the equilibrium of the electrophoretic and interparticle forces. In fact, electrophoresis has been used to measure the interparticle forces (Russel et al., 1989).

The results from the electrokinetic cell tests may partially explain the results of the 1964 USBM investigation discussed earlier (Stanczyk and Feld, 1964). The anode current density in their large scale test was 2.1 A m^{-2}, corresponding to a slower sedimentation velocity of ~ 2 mm h^{-1} from Fig. 7. It is also noted that the electrodes
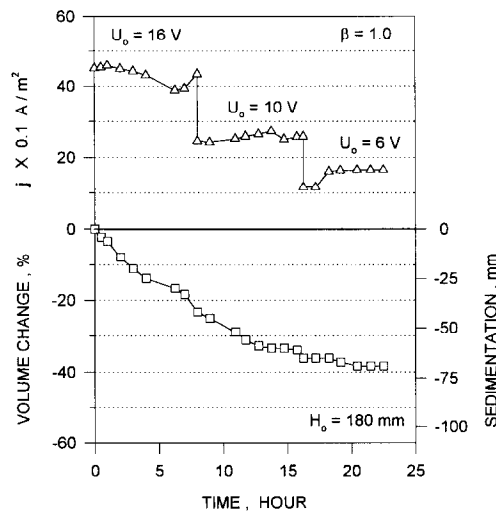
Fig. 3. Result of electrokinetic cell test: FPC-1.
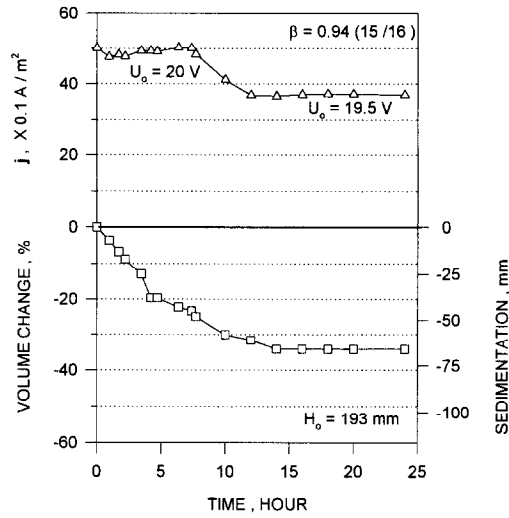
Fig. 4. Result of electrokinetic cell test: FPC-2.

were arranged vertically, inducing the horizontal movement of clay particles. All of these were likely the cause of slow dewatering.

By applying an intermittent current, the total power consumption is reduced to a fraction of that under a constant current. The volume change per unit power consumption (% per kWh) in the cell tests is plotted in Fig. 8 against the ratio β defined as

$$\beta = \frac{\text{power ON time}}{\text{power ON + OFF time}}$$

As shown in Fig. 8, the application of intermittent current did improve the efficiency of
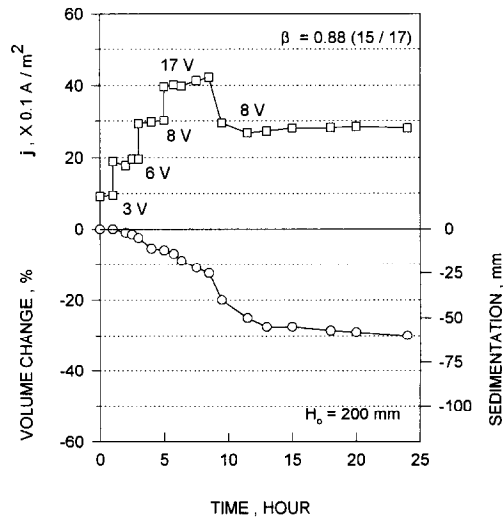
Fig. 5. Result of electrokinetic cell test: FPC-3.
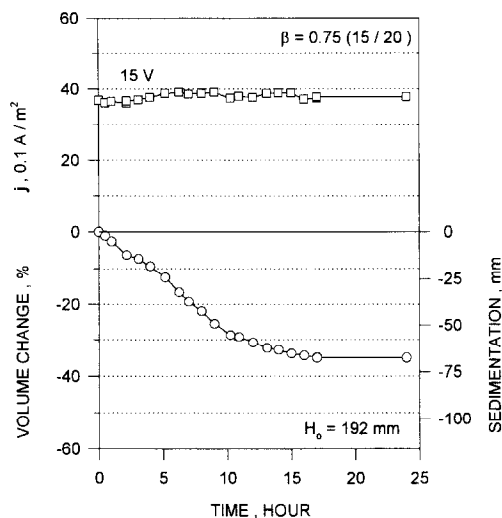
Fig. 6. Result of electrokinetic cell test: FPC-4.

electrokinetic sedimentation. Test FPC-4 with 15 min ON and 5 min OFF produced the most efficient dewatering effects.

As shown in the electrokinetic cell tests, the velocity of electrokinetic sedimentation of the phosphate clay suspensions was dominated by the applied current density. On the other hand, applications of intermittent current at proper intervals improved the efficiency of electrokinetic dewatering significantly.

3.5. Results of model tank test

In the model tank test No. FPC-H5, the initial solid content of the clay suspension was 12.7% at the end of gravitational sedimentation. The total volume of the clay suspension was 4254 cm^3 with an initial height of 12.5 cm. Heating was detected at the
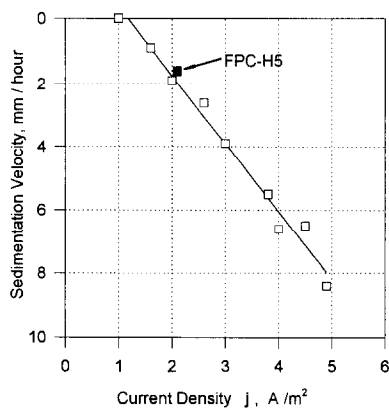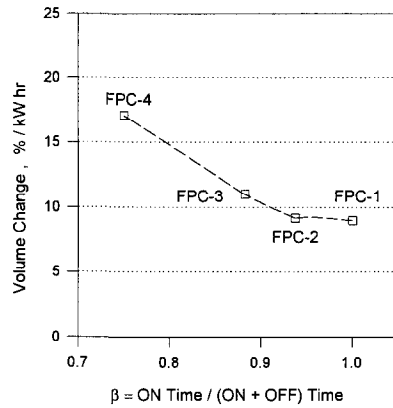

Fig. 7. Sedimentation velocity.

Fig. 8. Effect of intermittence.

bottom electrode pins at voltages higher than 25 V and is attributable to the converging electric field at the electrode pins. Therefore, the applied voltage was set at 25 V with intermittence $\beta = 0.71$ (5 min ON and 2 min OFF) to reduce energy loss by heating effects. The top electrode mesh was adjusted during testing to be on top of the mudline. In Stage 1, the top mesh served as the cathode and the bottom pins as the anode. The mudline was measured periodically at six locations of equal intervals along the length of the tank. Fig. 9 depicts the mudline profile after 31 h. A gap 2.25 cm deep and approximately 2 cm wide formed at the left-hand-side wall of the tank, similar to that in the cell tests (Fig. 2). The mudline underneath the top electrode mesh was horizontal, showing uniform sedimentation. Beyond the electrode mesh, the mudline sloped up toward the wall which is consistent with the less intensive electric field beyond the coverage of the top electrode. A crack occurred under the right edge of the electrode
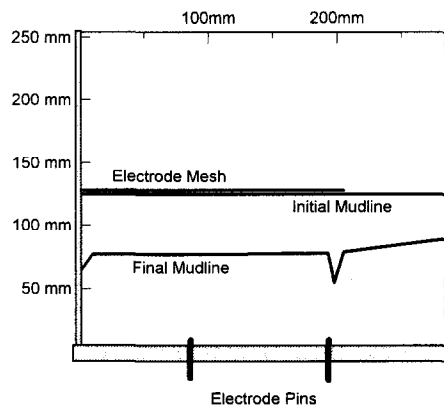

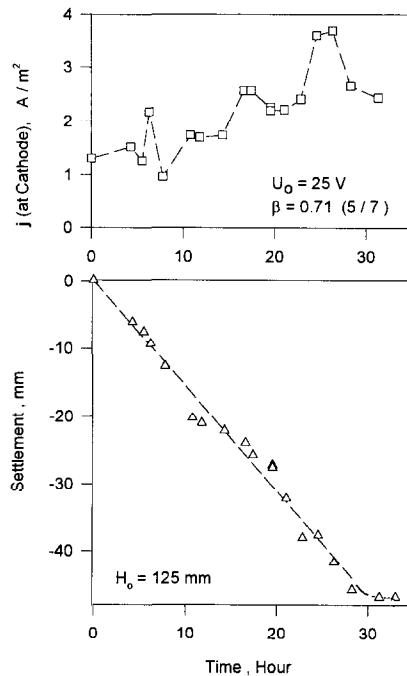Fig. 9. Soil profile after sedimentation in model tank test FPC-H5.

Fig. 10. Result of test FPC-H5, Stage 1: sedimentation.

mesh, approximately 0.4 cm wide and 1.1 cm deep. Fig. 10 presents the settlement and current density versus time. Because the distance between the top and bottom electrodes reduced with the descending mudline, the current density increased with time. For approximately 30 h, the sedimentation velocity remained constant at 1.7 mm per hour, yielding good agreement with the results of the electrokinetic cell tests as shown on Fig. 7. The average settlement was 4.9 cm at the end of Stage 1. The water collected in this stage was 1659 mL, representing a volume change of 39%. The average solid content at the end of Stage 1 was 29%, representing an increase of 128%.

The water samples were collected at the top of the tank for chemical analysis during Stage 1 testing. Cationic and anionic concentrations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cu^{2+}, Fe^{3+}, Cl^-, SO_4^{2-}, and PO_4^{3-}) were measured using a Phillips PU 9100X atomic absorption spectrophotometer (AAS) and a Dionex DX 2010 ion chromatograph (IC). As shown in Fig. 11a, the pH of water collected at the top cathode increased rapidly to 10.3 within three hours, but reduced to 6.9 after 31 h treatment which is attributed to the advection, diffusion and migration effects of the pH gradient generated by electrokinetics (Acar et al., 1994). Fig. 11b and Fig. 11c show that at pH ∼ 10 and above, the concentrations of Ca^{2+} and Mg^{2+} reduced to nearly zero due to formation of metal elements and precipitation of calcium hydroxide ($Ca(OH)_2$) and magnesium hydroxide ($Mg(OH)_2$), whereas when the pH decreased at the end of Stage 1, the concentrations increased again. The ionic migration induced by electrophoresis can be clearly seen
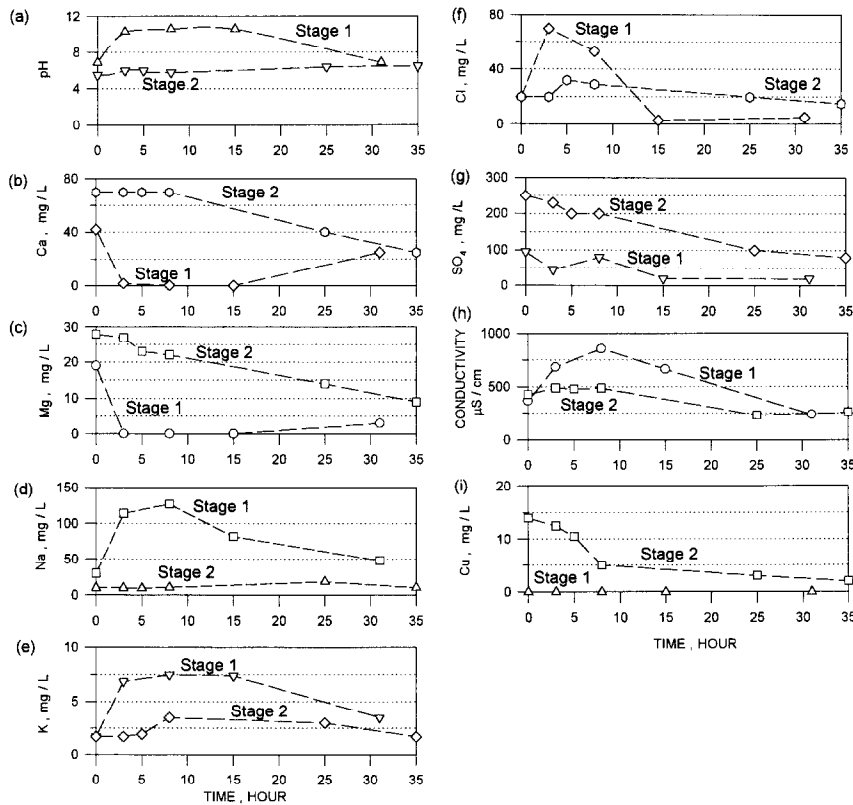
Fig. 11. Chemical changes during test FPC-H5.

through the increased concentrations of sodium and potassium and decreased concentrations of chloride and sulphate, as shown in Fig. 11d–Fig. 11g. The conductivity remained basically unchanged after 31 h, as shown in Fig. 11h. There were no copper ions (Cu^{2+}) present in the original solution, as shown in Fig. 11i. The polarity of the applied voltage was reversed to top-anode and bottom-cathode in Stage 2. The flow was observed immediately upon the reversal and equally distributed between the two drainage channels and was not affected by the asymmetry of the electric field, as shown in Fig. 12. The measured flow was proportional to the treatment time for the first 30 h. The electro-osmotic permeability of the phosphate clay was calculated as $k_e = 5.2 \times 10^{-6}$ cm^2 s^{-1} V^{-1} which was about one order of magnitude lower than the typical range of electro-osmotic permeabilities in successful field applications ($\sim 10^{-5}$ cm^2 s^{-1} V^{-1}) (Mitchell, 1993; Lo et al., 1991b), likely due to the significant smectites contents (Table 1). At the end of Stage 2 treatment, 493 mL of water were collected and the solid content was 34.1%, an increase of 18% compared to that at the end of Stage 1 (28.9%).

It was found from the authors' experience that maintaining contact between the electrodes and the soil is one of the most important factors in electrokinetic dewatering. During Stage 2 testing, the top-anode tended to lose contact with the clay and
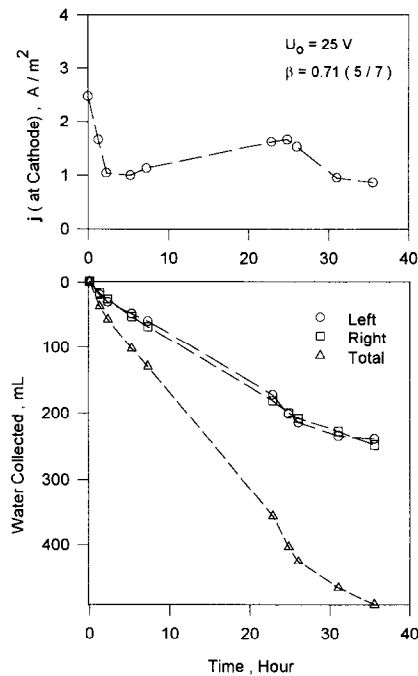
Fig. 12. Result of test FPC-H5, Stage 2: consolidation.

adjustment had to made from time to time, which was probably the reason for the current density fluctuation shown in Fig. 12.

The changes in water chemistry in Stage 2 are presented in Fig. 11. The data at time t = 0 represent the ionic concentrations after Stage 1 testing. After 36 h, the pH of water was neutralized to 6.7, as shown in Fig. 11a. The concentrations of Ca^{2+} and Mg^{2+} reduced significantly, as shown in Fig. 11b and Fig. 11c. Fe^{3+} was not detected at the cathode even though corrosion was expected at the top-anode, which was probably because Fe^{3+} formed at the top steel anode was transported to the bottom cathode by electrophoresis and precipitated to insoluble iron-hydroxide $(Fe(OH)_3)$. The migration of ions under the electric gradient was reflected through the concentrations of Na^+, K^+, Cl^- and SO_4^{2-}, which were consistent with the direction of the electric field, as shown in Fig. 11d–Fig. 11g. The conductivity of the collected water was similar to the original solution, as shown in Fig. 11h. It is of particular interest that the concentration of Cu^{2+} was 14 mg L^{-1} at the beginning of Stage 2 due to corrosion of the anode, and reduced rapidly to 2 mg L^{-1} at the end of the treatment, as shown in Fig. 11i, Stage 2. Orthophosphate was not detected in either the original or the collected water after treatment.

In summary, for the model tank test, a total of 2152 mL of water (1660 mL from Stage 1 and 493 mL from Stage 2) was removed from the clay suspension of initial volume of 4250 cm^3 over a period of 67 h, representing a total volume reduction of 49%, in which 39% was achieved during sedimentation and 10% during electro-osmotic

dewatering, respectively. The solid content increased to 34% from an initial 13%, representing an increase of 162%. The overall chemical effects in the process were fairly insignificant because of the neutralizing effects of polarity reversal. The power consumption over the 67 h of treatment was estimated at 16.5 kWh per cubic meter of clay suspension in which 46% was consumed during the sedimentation stage and 54% during the electro-osmotic dewatering stage, respectively. It may be concluded that electrokinetic sedimentation was very effective in the dewatering process for the dilute phosphate clay suspension. A volume reduction of about 40% was achieved in less than 30 h with power consumption of 7.6 kWh m^{-3}. However, after sedimentation was complete, the resulting electro-osmotic consolidation was less efficient, attributable primarily to its extra fine grain size and mineral composition.

4. Conclusions

The principles of electrokinetic dewatering consist of electrophoresis, dielectrophoresis and electro-osmosis. The factors governing the success of an electrokinetic dewatering treatment include the material properties, electrode configurations and operation systems, which need to be investigated thoroughly prior to an application. Electrokinetic dewatering of a phosphate clay suspension from Florida was investigated in an electrokinetic cell and in a model tank. The results demonstrated that the sedimentation velocity was controlled by the applied current density. The techniques of intermittent current and polarity reversal improved the effectiveness and efficiency of electrokinetic dewatering, reduced power consumption and neutralized adverse effects of electrode reactions.

Acknowledgements

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