Abstract

The treatment and disposal of sewage sludge is one of the most problematical issues affecting waste water treatment in the developed world. The traditional outlets for sewage sludge are to spread it on agricultural land, or to form a cake for deposit to landfill or incineration. In order to create a sludge cake, water must be removed. Existing dewatering technology based on pressure can only remove a very limited amount of this water because of the way in which water is bound to the sludge particles or flocs. Several researchers have shown that electrokinetic dewatering of sludge is more efficient than conventional hydraulically driven methods. This involves the application of a D.C Voltage across the sludge, driving water under an electrical gradient from positive (anode) electrode to negative (cathode) electrode. However, there have been several reasons why this technique has not been adopted in practice, not least because the, normally metallic, anode rapidly dissolves due to the acidic environment created by the electrolysis of water.

This paper will describe experimentation using electrokinetic geosynthetics (EKG): polymer-based materials containing conducting elements. These have been used to minimise the problem of electrode corrosion and create a sludge treatment system that can produce dry solids contents in excess of 30%. It
will suggest different options for the treatment of sludges both *in situ* in sludge lagoons and windrows, and *ex situ* as a treatment process.

**Keywords:** Sewage Sludge, Dewatering, Electrokinetic Geosynthetics
1.0 Introduction

It is well understood that the dewatering of sewage sludge is one of the most challenging technical tasks in the field of wastewater engineering [1] and all existing methods have severe limitations. These limitations may be attributed to the different physical states of water associated with the sludge and the manner with which they are bound to the sludge flocs. According to Smollen and Kafaar [2], water exists in the following physical states:

1. Free: water not associated with solid particles
2. Interstitial, capillary: mechanically bound water which is trapped in the flocs
3. Vicinal: physically bound multiple layers, held tightly to the particle surface by hydrogen bonding
4. Chemically bound: water of hydration

In addition, some sludges such as digested and activated sludges have a substantial intracellular component. Current dewatering methods are based on the use of mechanical pressure or centrifugation to cause the free water in the system to flow. This is performed by feeding a liquid sludge into a machine (centrifuge, belt press, etc.). This water can then be removed by mechanical means. More dewatering is achieved by exerting a greater and greater pressure. However, mechanical effects alone cannot achieve a sufficiently high potential to drive the interstitial water through the very narrow pore spaces and removal of interstitial water through mechanical means is extremely limited. Vicinal and chemically bound waters are not removed at all by mechanical means. Therefore, once a cake has been formed, however bad the quality, there are few ways of dewatering it further. Currently only potential gradients produced by thermal methods are sufficiently high to remove interstitial and vicinal waters, involving high capital and operating costs. Electrokinetic techniques offer one potential cost-effective solution. The objective of the work described herein was to establish the susceptibility of a range of sludge materials to electrokinetic dewatering and to explore different means of application using electrokinetic geosynthetics (EKG).
1.1 Electrokinetics

Electrokinetic techniques have been developed for treatment of clay soils, since their introduction as a construction technique in 1939. Electrokinetics, for these applications, may be defined as the application, or induction, of an electrical potential difference across a soil mass containing fluid, or a high fluid content slurry/suspension, causing or caused by the motion of electricity, charged soil and/or fluid particles.

Electrokinetic phenomena are the result of the coupling between hydraulic and electrical potential gradients in fine grained soils [3, 4, 5, 6]. These phenomena occur due to the presence of the diffuse double layer around the fine grained soil particles and involve the movement of electricity, charged particles and fluids [5].

Electrokinetic phenomena may be defined in terms of five categories. Of these, the three most relevant are defined below and illustrated in Figure 1:

- **Electromigration/Ion migration** - Applied electrical potential difference induces ion migration within the fluid phase of a charged particle matrix.
- **Electrophoresis** - Applied electrical potential difference induces movement of suspended colloidal particles within a fluid medium.
- **Electroosmosis (E-O)** - Applied electrical potential difference induces fluid flow in a charged particle matrix.

Typically electroosmotic dewatering of clay soils is of the order of 1 to 4 orders of magnitude faster than hydraulic dewatering, with a typical value of electro-osmotic permeability ($k_e$) for a clay soil being $10^{-5}$ cm$^2$/Vs, as opposed to hydraulic permeability which ranges from $10^{-9}$ m/s to $10^{-5}$ m/s for silts and clays. Actual values of $k_e$ and $k_h$ for a range of soils are shown in Table 1. The greatest advantage to be gained from electrokinetic dewatering over hydraulic dewatering is when the ratio of $k_e/k_h$ is high.

Like clay particles, sludge particles have a pH dependent surface charge, which is frequently negative. For this reason they too develop a diffuse ‘double layer’ of water surrounding the particles with the
characteristic zeta potential at the boundary between the fixed and mobile portions of this layer. Because
the flow of water induced by an electrical potential difference is not limited by pore size, electro-osmosis
has the potential to remove interstitial water from the sludge flocs, thus greatly improving dewatering
efficiency. Previous research (see section 1.2), which has concentrated entirely on improving various
dewatering machines, has showed that sludges are shown to vary in electrokinetic performance, but this
was not backed up by characterisation of the fundamental electroosmotic parameters e.g. $k_e$
(electroosmotic permeability), with the exception of Yan & Weng [7] who noted a $k_e$ value about 5 times
that of many soils.

1.2 Previous work

The idea of using electrokinetic techniques to dewater sludges is not new and has been investigated by
several researchers ([2, 8, 9]. The majority of these have concentrated upon the use of electro-osmosis to
enhance the dewatering capabilities of a mechanical process and have incorporated, for example,
electrically conducting rollers into a belt press. Other studies have concentrated on laboratory studies
using cake materials.

The major drawback with these studies is their practical application. If E-O is to be used only in
conjunction with mechanical pressure this severely limits its application within the overall framework of
sludge and wastewater treatment. The requirement for mechanical pressure would mean that it could not
be applied, for instance, to treat sludge lagoons in situ. Researchers who have investigated the effects of
E-O on cake in the laboratory, have not suggested a means of full-scale, practical implementation.

Another major deficiency is that all studies have used metallic electrodes. Electrolysis of water at the
electrodes always produces acidic conditions at the anode which contributes to rapid corrosion of the
metallic electrode. Within a relatively short period of time, the corrosion reduces the electrical contact
with the soil and electrical efficiency is reduced. The inability of a metallic electrode to act as an
effective drain also means that single polarity treatment, so that the final product is extremely
heterogeneous.
1.3 EKG Concept

EKG comprises conducting elements coated in a corrosion-resistant material, incorporated into a geosynthetic material. This patented design has overcome the problem of electrode corrosion. By encasing the metallic filaments in a relatively inert material, electrode corrosion is effectively managed or eliminated. By forming the electrode as a geosynthetic, EKG overcomes the problem of removing clean water by utilising the drainage and filtration functions of geosynthetics. Their ability to take on a wide variety of shapes and forms means that they can be manufactured to suit a range of different applications. It is envisaged that EKG could be applied in several ways:

- installed as vertical ‘wicks’ into sludge lagoons and used to draw water to the surface, removed by pumping, and discharged;
- installed as a combination of basal grid and fabric cover to increase dewatering rates in windrows; and
- formed as the fabric in a belt or filter press to improve dewatering performance.

2.0 Lagoon Applications

Electroosmotic consolidation could be applied practically in real situations by adapting the technology known as prefabricated vertical drains (PVD) or wick drains. These are used routinely to consolidate soft soils in situ. PVDs work by creating short pathways for water to flow out of a low permeability substrate such as fine grained lagoon waste. Using the traditional PVD approach, water flow is caused by creating a pressure difference between the PVD and the material to be consolidated. This pressure difference is achieved by placing a load (usually in the form of a layer of sand and gravel several metres thick) over the surface of the material to be consolidated. This process can take many months or even years to complete and is limited by the hydraulic permeability of the materials and the rate at which the overlying load material can be placed onto a weak substrate (staged loading).

Electroosmotic PVDs or ePVDs utilise the higher flow rates that are achievable by E-O without any additional load. The advantages of this approach are that it does not require the double-handling of large quantities of material demanded by the application of any load and it is much faster. The speed advantage
derives from the fact that electroosmotic permeability is higher than hydraulic permeability (for materials such as silts, clays and sludges), and that because no load is required, the full flow rate can be achieved immediately rather than needing to wait for gradual improvements in strength before additional load is applied as is the case with ‘staged loading’. A staged approach is normally required as soft, lagooned materials are too weak to support a significant load.

Part of the approach with ePVDs is the reversal of polarity to create homogeneous gains in material strengths between anodes and cathodes. EKG electrodes are designed to operate equally effectively as cathodes or anodes and are thus ideally suited to secure the advantages offered by polarity reversal.

### 2.1 Laboratory Testing

Tests were performed on a cold digested thickened lagooned sewage sludge with an initial dry solids content of approximately 15%. This sludge had been resident in the lagoon for approximately 3 years. Tests were additionally performed on a similar sludge that had been resident for over 80 years. That work is presented elsewhere by Glendinning and Walker [10] and concluded that the dry solids content could be increased from about 19% to 42%, accompanied by a significant increase in shear strength from less than 1kPa to 29kPa and a 57% reduction in volume.

Tests were performed to determine the ability of the materials to support E-O and the degree of consolidation that may be achieved by E-O. The coefficient of electroosmotic permeability, kₑ, is used as an indicator of a materials ability to support E-O. The testing method used was non-standard and has been developed at Newcastle University. It comprised measuring the flow of water caused by E-O under constant electrical gradient with a constant supply of water to the anode under zero hydraulic head in the test cell illustrated in Figure 2. E-O consolidation tests were performed in a similar experimental apparatus, with the water supply to the anode switched off, i.e. operating under ‘closed anode’ conditions. An initial test of 3 days duration was performed, followed by a longer test of 3 weeks duration. All tests were undertaken using an applied back pressure of 50kPa and an applied voltage gradient of 1V/cm. The control test had zero applied voltage.
Both sets of tests were performed using parallel copper disc electrodes. Three repeat tests (A, B and C) were performed due to the variability of the initial material dry solids.

2.2 Results

The sludge demonstrated a $k_e$ value of $1.5 \times 10^{-5}$ cm$^2$/Vs, which compares very favourably with the types of clay soils that are most amenable to this treatment (see Table 1).

The results of the 3-day consolidation tests are shown in Figure 3. This illustrates the volume of water extracted from the sample with time and demonstrates the very marked difference between the control (with no voltage applied) and the samples subjected to an electric field.

At the end of the 3-day test the control sample had a dry solids content of 16% with virtually no change in volume of the sample; the maximum dry solid content of the E-O treated samples was 27% (at the anode) accompanied by an average 10% reduction in volume over the sample. Results of the, 21-day tests (on A and B samples only) are summarised on Table 2, producing average solids contents of 27% (B) and 23% (A).

The tests concluded that the sludge is a suitable substrate for effective E-O dewatering, which proved considerably more effective than hydraulically driven dewatering alone. Treatment could produce an overall volume reduction of between 40% and 50% over a period of 21 days.

2.3 Field Trial

The effectiveness of electrokinetic consolidation of lagooned sewage sludge cake by means of ePVDs was examined at pilot scale using two steel containers of 9.7m$^3$ capacity with tailor-made butyl liners were filled with approximately 8.5m$^3$ of sludge. The sludge was in a liquid state with a low shear strength (unmeasureable using a hand vane, but estimated to be approximately 1kPa) and a solids content of only 10.6%. Two electrode arrays were evaluated:
- Rectangular array with Anode-Cathode spacing of 0.9m and Anode- or Cathode-Cathode spacing of 0.4m
- Hexagonal array with spacings of 0.7-0.9m (in practice an equilateral spacing would be chosen; here the hexagons were distorted to suit the containers).

The electrodes were composite EKG Mk5 ePVDs, which comprised six different components including a central perforated drain, filter fabric, primary and secondary conducting elements, and integral and binding knitting yarns. The arrays were run at 30V, providing a voltage gradient in the order of 33V/m.

63 days of treatment, applying an intermittent voltage resulted in a reduction in volume of 23.0% for skip A and 29.7% for skip B. It is considered that the potential for reduction, however is much greater as the method used to remove water from the cathodes was not particularly efficient and significant quantities of water collected at the surface of the sludge adjacent to the cathode from where it flowed back to the anode and effectively recirculated around the system.

Shear strength was measured using a hand shear vane in a regular grid pattern across each skip. The average shear strength for skip A was 7kPa and 16kPa for skip B. A before-and-after photograph of the Skip B is shown in Figure 4. Again, it is felt that higher strengths can be achieved in the same time once the problem of water removal caused by the poor performance of the siphons is corrected.

Power consumption was calculated for the entire treatment period, from the readings made of current and voltage, to be 134 kWh/wet tonne and 105kWh/wet tonne for skips A and B respectively. However, it is felt to severely overestimate the amount of power required to treat this volume of soil if the overall treatment area is scaled up. This is due to the effect of the edges of the container, where there were no electrodes – in a full treatment the equivalent area of sludge would be influenced by a number of electrodes, just as the centre of the skips are being effected in this trial.
2.4 Conclusions

The laboratory testing has indicated that significant increases in shear strength and reductions in volume can be achieved by the application of E-O to lagooned sludges. The field trial has shown some improvement can be achieved by the application of E-O in situ using e-PVDs. However, some further development is required, particularly on the method of extracting the water from the cathodes before the full potential of E-O can be realised.

3.0 Windrow Applications

At present some humic sludge is treated by thickening, pressing (in a belt or filter press) and then drying in the open air in elongated stockpiles, or windrows. Wood waste is added to the ex-belt press sludge in the proportion of approximately 30 – 40% by volume. The addition of wood waste is carried out primarily to improve the mechanical handling characteristics of the sludge. The mixing of wood waste has a cost implication for acquiring the material, mixing it and handling the bulk product, which increases markedly in volume on addition of the wood waste.

The main objective of the study described herein was to examine the effects of E-O on the sludge with varying proportions of wood waste in order to explore if E-O dewatering would permit a reduction in the overall amount of wood waste that needs to be added to the ex-press sludge.

3.1 Laboratory Testing

Tests similar to those described above were performed on ex belt-press humic sludge. E-O consolidation tests were conducted over a period of 21 days with a cell back pressure of 25kPa and a voltage gradient of 0.5 V/cm with pure sludge samples mixed with varying proportions of wood waste (0%, 10%, 30%, and 50%). Control tests (with no voltage applied) were performed on the 0% and 50% mixtures.
3.2 Results

$K_e$ values ranged from $7.2 \times 10^{-5}$ to $2.0 \times 10^{-5}$ cm$^2$/Vs, indicating that the materials fully support E-O. This proved to be of the order of 500 times greater than the hydraulic permeability of the sewage sludge alone, but only 120 times greater that that of the sludge mixed with 50% wood waste. Figure 5 shows the comparisons in water discharge from each of the E-O tests. Although not plotted, control tests typically produced approximately 150ml of discharge during 21 days.

It is clear that the 10% wood waste mixture provided the best dewatering. This particular test showed a significant levelling off after 5 days, possibly due to the entrapment of gas produced adjacent to the electrodes. If this were the case, then further dewatering could be achieved in practice where gas is free to escape. The 0%, 30% and 50% tests appeared to be continuing to dewater after 21 days, although at different rates.

3.3 Field Trial

A field trial was conducted on humic sludge mixed with 33% by volume wood waste. A trial windrow was constructed which was 26m long, 5m wide at the base, and 2m high. EKG was installed in half of the length of the windrow, of which half was activated at 10V. An intermittent voltage was applied for a period of 3 months.

Post treatment exhumation of the windrow revealed significant differences in the properties of the different sections of the windrow. The active section exhibited significantly improved drainage and volume reduction (Figure 6) and microbial activity.

3.4 Conclusions

The broad relationships derived from the test programme show that E-O works best, theoretically and practically, for pure sludge, and its effectiveness decreases with additions of wood waste. A combination of E-O dewatering with a 10% (by volume) mixing of wood waste appears to optimise dewatering and strength improvements, thereby offering significant cost savings over existing practices. The field trial
has shown that significant improvements can be realised at full-scale for humic sludge mixed with 30% wood waste.

Although not explicitly tested in this programme, it also offers the potential of using green wood waste instead of dry wood waste. Currently this is impossible due to the high water content of green wood waste.

### Press Applications

Many types of sludges are currently dewatered using mechanical means. Examples include both belt and filter presses. Sludge is firstly thickened using a polymer flocculant before being mechanically pressed. For reasons described earlier, the degree of dewatering achieved by these means is limited, at best achieving dry solids contents in the region of 15-20%. The remit of this work was to investigate the potential for applying electrokinetics to press technology to improve the dewatering of sewage sludge.

#### 4.1 Laboratory testing

Similar tests to those previously described were undertaken, with the exception of the form of the electrodes, the thickness of the sample and the duration of the test. Electrodes were cut from woven polyester material and electrified with carbon fibre strips at spacings of 5mm, 10mm, and 20mm. In this way these electrodes had very similar electrical and filtration properties to those that would be used in an operating press.

The sludge tested included the same ex-belt press humic sludge that was tested as part of the lagoon trial described earlier (15% dry solids) and ex-drum thickener activated sludge further dewatered by hand pressure (7.6% dry solids). The test set-up used two separate voltages of 15V and 30V applied to a 15mm thick sample with a back pressure of 70kPa for humic sludge and 25kPa for activated sludge. The tests lasted for 20 minutes. The higher pressure was used to simulate typical pressure exerted in a belt press and the 20-minute duration was considered to be approximately two to three times the typical residence time of sludge in a belt press.
4.2 Results

The percentage dry solids achieved by treatment of the humic sludge after 20 minutes duration for the different electrode configurations and applied voltages is shown in Figure 7. This method calculates the dry solids in the material remaining in the cell from the volume of water collected. This calculation may underestimate % dry solids because some water removed by electrolysis is not accounted for and may therefore be regarded as conservative. The most effective of the tests were repeated (denoted with an R) to ensure repeatability of the dry solids achieved.

The results for similar tests on activated sludge are shown on Table 3.

These results, although apparently less encouraging than those for the humic sludge were achieved using a back pressure of only 25kPa. This was necessary due to the very fluid consistency of the initial sludge material meaning that higher pressures forced the entire sample through the filter material. This low back pressure is of considerable significance here because it means that all the effective dewatering is attributable to E-O alone.

A recent trial was conducted using a full-scale belt press fitted with EKG belts in which significant increases in solids content were achieved.

4.3 Conclusions

Results showed that the electrified belt materials acted as very effective electrodes and indicate that significant advantages can be gained in the dewatering efficiency of sewage sludge materials. Although the best improvements in solids content derived from testing electrodes with conducting elements spaced at 5mm and a potential of 30V the dewatering achieved appears to be more sensitive to applied voltage than to element spacing. These tests repeatedly produced solids contents of >30% after 10 minutes (the time representative of the residency within a belt press). It should be noted that this figure represents a conservative estimate of the solids contents. Tests on activated sludge produced solids contents up to
15.9%, again with the best results being produced from a combination of a 5mm conducting element spacing and an applied potential of 30V.

5.0 Discussion

Overall, the dewatering of sewage sludge will significantly reduce the volume of material either being deposited to landfill, or being transported for land spreading. Drying also increases the calorific value of sludge and offering greater potential for its use as an autothermic fuel. This work has shown that electrokinetic techniques can be used to dewater a range of different types of sewage sludge and points towards three different possible applications.

Dealing with an old sludge lagoon has generally meant removing the sludge altogether and clearing the site. Left to itself a sludge lagoon, deeper than say one metre, which has been deposited as a liquid, will never dry out. A crust will form on it, with plant growth that will dry out the crust to some extent. However below this the sludge will generally not thicken beyond perhaps 12 to 20% dry solids, and may well be wetter. Transpiration and evaporation will be balanced by rainfall. Attempting to remove such material is difficult since it is too thick to pump and will contain tufts of grass, etc., and is too thin to shovel since it will slump completely. Prior to the arrival of the EKG process only two methods for stabilising a lagoon in situ were available; either mixing in more and more dry material until the lagoon was effectively solid; or employing a specialist contractor to mix quicklime or cement into the sludge to stiffen it. This second option is very expensive and would be unlikely to be economic unless the site of the lagoon had very important development potential.

It is envisaged that EKG will be installed into lagoons containing this type of material by firstly creating a working platform over the surface of the lagoon using a stiff geogrid overlain by a granular capping. From this working platform EKG 'wicks' will be lanced vertically through to the base of the lagoon at 1-2m centres. Water will be drawn to the cathodes from where it will be pumped and discharged. The design of an installation such as this will require initial laboratory characterisation of the sludge, followed by an on-site pilot-scale test. As such it offers a potentially economic solution to treating sewage (or, indeed any other waste) lagoons in situ.
EKG can be applied to the dewatering of compost windrows. The technique is to form and thoroughly mix the windrow then to insert cathode electrodes across the bottom and insert anode electrodes near the top. The passing of the current would cause water to move downwards to the lower electrodes, which would form channels for it to leave the windrow. Results from the laboratory testing suggest that the amount of wood waste currently added to the sludge can be reduced by 80%. This, coupled with the faster rate of drying has the potential to significantly reduce the cost of these operations.

Significant improvements can be made to belt or filter presses by forming part of the machine as an EKG. In so doing, dry solids of greater that 30% appear to be achievable. This is a significant advance over previous proposals of electrified steel belts or drums as it overcomes the problems of filtration and longevity. The results show, within the limits of the above tests, that varying the voltage gives the greatest control over dewatering performance. Therefore, in an operating system this parameter will be of great value and may be optimised to suit the electrical and E-O characteristics of different sludges.

6.0 References


Figure Captions

Figure 1 Electrokinetic Effects

Figure 2 Electosmotic Cell

Figure 3 Volume of discharge water during 3 day E-O consolidation test

Figure 4 Skip trial before and after treatment

Figure 5 Water discharged from E-O tests on ex-belt press humic sludge (mixed with varying proportions of wood waste)

Figure 6 Windrow trial, showing (a) increased settlement at crest and (b) increased drainage at the base

Figure 7 Humic sludge: % dry solids from discharge
### Tables

**Table 1. Typical values of $k_e$ and $k_h$ (After[5])**

<table>
<thead>
<tr>
<th>Material</th>
<th>Moisture content</th>
<th>$k_e \times 10^{-5}$ (cm²/Vs)</th>
<th>Approx. $k_h$ (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine sand</td>
<td>49.7</td>
<td>4.1</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Clayey silt</td>
<td>31.7</td>
<td>5.0</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Kaolin</td>
<td>67.7</td>
<td>5.7</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>London Clay</td>
<td>52.3</td>
<td>5.8</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>Na montmorillonite</td>
<td>170</td>
<td>2.0</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Na montmorillonite</td>
<td>2000</td>
<td>12.0</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

**Table 2 Summary of long term consolidation tests**

<table>
<thead>
<tr>
<th></th>
<th>Test A</th>
<th>Test B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial moisture content</td>
<td>621 %</td>
<td>574 %</td>
</tr>
<tr>
<td>% dry solids</td>
<td>13.9% ds</td>
<td>14.8% ds</td>
</tr>
<tr>
<td>Test duration</td>
<td>21 days</td>
<td>21 days</td>
</tr>
<tr>
<td>Volume of extracted water</td>
<td>837 ml</td>
<td>1083 ml</td>
</tr>
<tr>
<td>% dry solids at cathode</td>
<td>31.8%</td>
<td>38.9 %</td>
</tr>
<tr>
<td>% dry solids at anode</td>
<td>64.5%</td>
<td>72.5%</td>
</tr>
<tr>
<td>Total volume reduction</td>
<td>-40%</td>
<td>-51.7%</td>
</tr>
</tbody>
</table>

**Table 3 % dry solids after 20 minutes, activated sludge**

<table>
<thead>
<tr>
<th>Electrode design and applied voltage</th>
<th>2.5mm 15V</th>
<th>5mm 30V</th>
<th>10mm 30V</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge (ml)</td>
<td>63.00</td>
<td>126.00</td>
<td>93.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Displacement (mm)</td>
<td>-0.07</td>
<td>-1.89</td>
<td>-1.32</td>
<td>0.00</td>
</tr>
<tr>
<td>% dry solids (discharge)</td>
<td>10.28</td>
<td>15.89</td>
<td>12.36</td>
<td>7.60</td>
</tr>
</tbody>
</table>
Figure 1

Electro-osmotic Water Flow
Electro-phoretic Particle Flow

**Electrolysis**

2H₂O → 4H⁺ + O₂(g) + 4e⁻  
[H⁺] increases  
PpH decreases

**Electrolysis**

2H₂O + 2e⁻ → H₂(g) + 2OH⁻  
[H⁺] decreases  
PpH increases

D.C. Power Supply

ANODE  |  CATHODE

Acid Front  |  Base Front

OH⁻  |  H⁺

A⁻  |  M⁺

Ion migration
Figure 2

- Transducer - measuring volume change
- From pressure system
- To measuring cylinder - fluid from plunger
- Electrical connection to anode
- Fluid flow to measuring cylinder
- Perspex cylinder
- Disk electrode (cathode)
- Perspex drainage disk
- Sample
- 150mm
- Anode
- Electrical connection to cathode

Not to scale
Figure 3
Figure 4

The graph shows the discharge over time for different percentages. The x-axis represents time in days, ranging from 0 to 20, and the y-axis represents discharge in milliliters, ranging from 0 to 600. The graph includes lines for 0%, 10%, 30%, and 50% discharge, each represented by different markers.

- The 0% line starts at the origin and shows a steady increase.
- The 10% line starts from a higher point and also shows a steady increase.
- The 30% line starts even higher and increases steadily.
- The 50% line starts the highest and increases at the steepest rate.

The data indicates that the discharge increases significantly over time, with higher percentages starting at higher initial discharge levels.
Figure 7

The graph shows the percentage of dry solids over time for different conditions. The conditions are labeled as follows:

- Control.A
- Control.B
- 5mm, 30V
- 5mm, 15V
- 20mm, 30V
- 20mm, 15V
- 10mm, 30V
- 10mm, 15V
- 10mm 30V R
- 5mm 30V R

The x-axis represents time in minutes, ranging from 0 to 20. The y-axis represents the percentage of dry solids, ranging from 0 to 70%.