DEVELOPMENT OF ELECTROOSMOTIC SLUDGE DEWATERING TECHNOLOGY

Final Report

by

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Report submitted to the
WATER RESEARCH COMMISSION

Stellenbosch
January 1995

WRC Report No. : 427/1/95
ISBN No. : 1 86845 163 1

EXECUTIVE SUMMARY

Objectives

The problems associated with sludge dewatering are widely appreciated and the search for improved dewatering techniques is being pursued worldwide, with new approaches and associated equipment regularly appearing on the market.

Recognising the importance of sludge handling and utilisation technologies the Water Research Commission entered into a two year contract with the CSIR Division of Water Technology to investigate the electroosmotic (EO) sludge dewatering which presents a novel approach in South Africa. This investigation had four objectives:

1. Literature review on the role of sludge liquid structure in sludge dewatering.

2. Laboratory investigation of electroosmotic dewatering and sludge behaviour when subjected to electroosmotic process.

3. Study of sludge dewatering using partly built (one stage) electroosmotic filter-belt scale model.

4. Investigation of sludge dewatering using the two stage electroosmotic filter-belt scale model.

Conclusions and recommendations

The literature review, which was undertaken as the first stage of the investigation, highlighted an important aspect of sludge behaviour and that is that the physical and chemical phenomena, which occur in the interface of the electric double layer, are indicative of the importance of the individual liquids fixed in the sludge particle. Better understanding of the distribution of water and of the forces that bind water within the sludge may lead to better dewatering performance. Inefficiency of mechanical dewatering in removing liquids held within electric double layer (minute capillary structures), can be overcame by dewatering enhanced by electroosmosis.

From laboratory experimental results it was concluded that electroosmotic dewatering has the ability to remove the liquid which is hard to remove using conventional methods.

Scale model of a filter-belt device, in combination with electroosmotic dewatering was developed and partly built. It was found that the experimental results support the preceding laboratory results. It seems that EO can be particularly effective in dewatering of biological or chemical gelatinous and fine-particle sludges too difficult for mechanical dewatering.

Significant advantage of EO can be observed when applied in filtration processes. Blinding of the filter media, which is recognised as a major drawback of filtration, is markedly reduced by EO.

Upon completion of the electroosmotic two stage scale model and experimental trials the preceding findings were confirmed.

The uniqueness of the concept has been proven in the following respects:

1. The operational criteria can be tailored to each type of sludge which will provide greater flexibility in practical dewatering applications.

2. During electroosmotic dewatering major changes in cake structure take place which produce crumbly cake consistency, suitable for beneficial re-use or safe and cost-effective final disposal. This specific sludge cake consistency cannot apparently be achieved by conventional dewatering methods.

3. The success of electroosmotic dewatering depends on electrical characteristics of the sludge. It is found that all investigated samples of waste activated sludges could be dewatered to an average solids concentration of 15% and consistency of a crumbly sludge cake which can be stacked for further air drying or easier and cheaper transport.

4. Efficiency of electroosmotic dewatering improves with the increase in initial sludge solids concentration. Therefore, sludge needs to be prethickened to a highest possible solids concentration, prior subjecting it to EO dewatering. Because there is large installed capacity of centrifuges and vacuum filters, EO filter-belt press can be used to reduce moisture content of previously formed sludge cake.

5. Significant reduction in polyelectrolyte use is attributed to electroosmotic dewatering. Minimum dosage of 0,5 to 2,0 kg/Tds is recommended to be used for activated and anaerobically digested sludges respectively.

6. The comparison of energy consumption of the three commercially available dewatering machines, i.e. centrifuge, filter press and filter-belt press, with electroosmotic scale model of filter-belt press illustrates that the range of 0,08 to 0,13 kWh/kgds attributed to the EO dewatering does not exceed the values reported for the full-scale equipment.

7. The most recent experimental trials proved that the EO filter-belt can produce sludge cake of solids concentration reaching 45 percent which complies with a most stringent world standards.

8. The EO experimental filter-press, being a scale model of the full-scale plant, can supply only general criteria to be used in the final design of a prototype pilot-plant due to it's practical limitation which preclude valid insight into variables such as throughput, belt speed, voltage, gap between belts, etc. The trials of the proposed technical scale pilot-plant will be the occasion when questions regarding operational variables can be investigated and answered.

The above findings are sufficient to justify the investment in a prototype pilot-plant which, upon incorporation of structural and mechanical improvements, can be optimised for factory production and sales as a proven unit.

Since this report was first written, further developments concerned with design and construction of the prototype pilot-plant have taken place.

ACKNOWLEDGEMENTS

The writers wish to express their gratitude to the following persons for their contribution to the contract research work reported here :

* André Vogel and Associates for translating the electroosmotic dewatering concept into design and for supervision of the scale model construction.

* The members of the Steering Committee of the project:

Dr S A Mitchell	-	Water Research Commission (Chairman)
Mr H G J Beekman	-	Cape Town City Council
Prof G Ekama	-	University of Cape Town
Mr F P Marais	-	Water Research Commission (Committee Secretary)
Mr A R Pitman	-	Johannesburg City Council

FINAL REPORT to the WATER RESEARCH COMMISSION
on a two year exploratory study on the
DEVELOPMENT of ELECTROOSMOTIC SLUDGE DEWATERING TECHNOLOGY

(1992 - 1993)

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LIST OF SYMBOLS

Symbol	
A	Ampere
AD (1)	Anaerobic Digestion (primary sludge)
AD (2)	Anaerobic Digestion (mixture primary & activated)
AeD	Aerobic Digestion
BF	Biological Filter
CST	Capillary Suction Time (s)
DAF	Dissolved Air Flotation
E	Potential drop between the electrodes (V)
E_w	Energy requirement ($kWh.m^{-3}$)
e	Dielectric constant of the interstitial liquid
EO	Electroosmosis
G	Centrifugal acceleration in gravities
K_o	Electroosmotic coefficient
L	Distance between electrodes (m)
P	Pressure drop - Poisseuille's equation (Pa)
Q	Volume of filtrate removed by electroosmosis (m^3)
Q_o	Initial volume of sludge to be dewatered (m^3)
R	Specific electric resistance ($\Omega m^2.m^{-1}$)
R_h	Hydraulic retention time in digester (d)
R_s	Solids retention time - sludge age (d)

SRF	Specific resistance to filtration ($m.kg^{-1}$)
t	Time of electroosmosis (min)
V	Applied voltage (V)
W	Watt
WAS	Waste activated sludge
WAS (1)	Waste activated sludge (N removal)
WAS (2)	Waste activated sludge (P & N removal)
η	Viscosity of the suspension at the ambient temperature (Pa.s)
λ	Specific conductivity (mS)
ξ	Zeta potential (mV)
Z	Zimpro sludge (heat treated primary sludge)

SLUDGE SAMPLE NUMBER

1	WAS (waste activated sludge) - DAF, Athlone
2	Primary and secondary AD (primary sludge), Athlone
3a, 3b	WAS (1), a - municipal, b - industrial, Atlantis
4a, 4b	WAS (1), a - municipal, b - industrial, Bellville
5	WAS (1) DAF, Borcherd's Quarry
6	AeD - DAF, Borcherd's Quarry
7	WAS (2) - DAF, Cape Flats
8	Primary AD (mixture of pasteurised raw and waste activated sludges), Cape Flats
9	WAS (1) - DAF, Mitchell's Plain
10	Primary and secondary AD (mixture of primary and secondary sludges), Mitchell's Plain
11	WAS (1) - gravity, Scottsdene
12	WAS (1) - gravity, Stellenbosch
13	WAS (2) - Package Plant
14	Waterwork alum sludge, Blackheath
15	Waterwork alum sludge, Steenbras
16	Waterwork ferric sulphate sludge, Voëlvlei
17	Industrial waste, barium sulphate slurry
18	Zimpro heat treated primary sludge
19	Kraaifontein anaerobically digested primary
20	WAS (1) after centrifugation, Mitchell's Plain

1. INTRODUCTION

Sludge management is increasing in both cost and complexity all over the world. At present it is estimated that some 50 % of the operating costs of wastewater treatment are related to sludge stabilisation, dewatering and disposal. The reduction in sludge quantity for final disposal by increasing the solids content during dewatering processes is one of the most important aspects of sludge management.

Municipal sludges are hydrophillic by nature and typically have moisture contents of 98 to 99,7 %. This moisture is difficult to remove. In recent times the disposal of increasingly large volumes of municipal sludges has resulted in steady increase in cost.

The majority of the larger wastewater treatment plants make use of mechanical dewatering such as centrifugation, belt and pressure filtration - complex and expensive methods generally dictated by the fact that municipal sludges do not respond well to dewatering procedures. One would expect that with mechanical dewatering the water content of sludge could be reduced, for example, from 85 to 55 %, but this in many instances is not achieved even with the aid of chemical conditioners. The cost of energy, plant depreciation and maintenance and in particular chemical additives create a very heavy financial burden. Usually these effects become apparent only after the plant is put into operation, when the sludge does not respond to treatment, and the operators are forced to apply crisis procedures, usually high and costly chemical addition.

The problems associated with sludge dewatering are widely appreciated and the search for improved dewatering techniques is being pursued worldwide, with new approaches and associated equipment regularly appearing on the market. One of the unconventional approaches to sludge dewatering is electroosmosis (EO). Major theoretical research on design and operation of equipment practically implemented in electroosmotic dewatering of sludges took place quite recently in Japan (Yoshida and Yukawa, 1992). In South Africa electroosmotic dewatering presents a novel approach.

In 1991 the Water Research Commission drew up a Master Plan for future research on sanitation in South Africa, which included an exhaustive list of potential projects, and identified those areas to which priority should be given. Among the priorities was proposal to improve sludge handling and utilisation technologies.

CSIR Regional Water Research Laboratory in Bellville (now Watertek in Stellenbosch) has been involved with study on sludge characterisation for cost-effective sludge dewatering and unconventional dewatering techniques for a number of years. Laboratory investigation of the application of EO for sludge dewatering started in 1988. Based on laboratory results it was found that the EO phenomenon facilitates dewatering of troublesome municipal sludges. The idea of incorporating EO into filter-belt press was patented in 1990. First stage of the scale model was constructed and commissioned at the beginning of 1992.

The partly built scale model of the EO filter-belt press was installed at the new location of Watertek in Stellenbosch. Financial support was sought from the Water Research Commission to sponsor further development of the new technology.

A two year contract (1992, 1993) was subsequently negotiated between the WRC and Watertek, with the main objectives of performance evaluation and examination of potential application of the electroosmotic filter-pressing for dewatering of activated, anaerobically digested and waterworks sludges.

The dewatering plant, as delivered, was only a single stage electroosmotic unit and did not employ the patented staged configuration. Additional mechanical stage was installed in June 1993 after which extensive investigation was undertaken in order to produce possibly most informative experimental study.

There are four objectives of this investigation.

1. Theoretical background of the role of sludge liquid structure in sludge dewatering.

   To appreciate the improved performance of electroosmotic dewatering a better understanding of the character of water-sludge matrix and sludge physical properties are essential. Investigation of the phenomena that occur in the interface of the electric double layer on the surface of sludge particle indicate the importance of the individual liquids fixed in sludge particles. Mechanical sludge dewatering cannot remove water which is held within the electric double layer. The water fractions which are strongly bonded to the surface of a sludge particle can only be removed by chemical, thermal or electroosmotic processes.

2. Laboratory investigation of electroosmotic dewatering.

   From laboratory experimental results it was concluded, that electroosmotic dewatering has the ability to remove sludge liquid which cannot be removed using conventional methods.

3. Study of sludge dewatering using partly built electroosmotic scale model. A scale model which incorporates EO into filter-belt press was partly built and experimental runs were conducted. The results provided not only

information for the next phase of the plant development but also valuable new insights into the difficult problems of sludge dewatering.

4. Investigation of sludge dewatering using the two stage electroosmotic scale model.

   The experimental results from the two stage scale model warrant the construction of a full-scale pilot plant, capable of being converted or developed into a production plant.

2. THEORETICAL BACKGROUND

2.1. Sludge - liquid phase

All sludges, organic and inorganic consist of a combination of solid phase with a certain quantity of liquid. Behaviour of this liquid is often wrongly assumed to be the same as that of ordinary water. There are different physical forms of water in sludge and these different forms play an important role in determining the ease or difficulty of phase separation.

The liquid fractions in sludge flock can not be classified merely as "free" and "bound". Assumption that water within a sludge-flock behaves like free water, and is characterised by the same physical and chemical properties as ordinary water, is not valid. Although the names given to the various water fractions have evolved over the years (Vesilind 1974, Moller 1983, Smollen 1986), the following description of different physical states appears to be the most appropriate (Fig 1):

- free: water not associated with solid particles;
- interstitial, capillary : mechanically bound water which is trapped in the flocs;
- vicinal: physically bound multiple layers of water molecules, held tightly to the particle surface by hydrogen bonding;
- chemically bound or water of hydration;

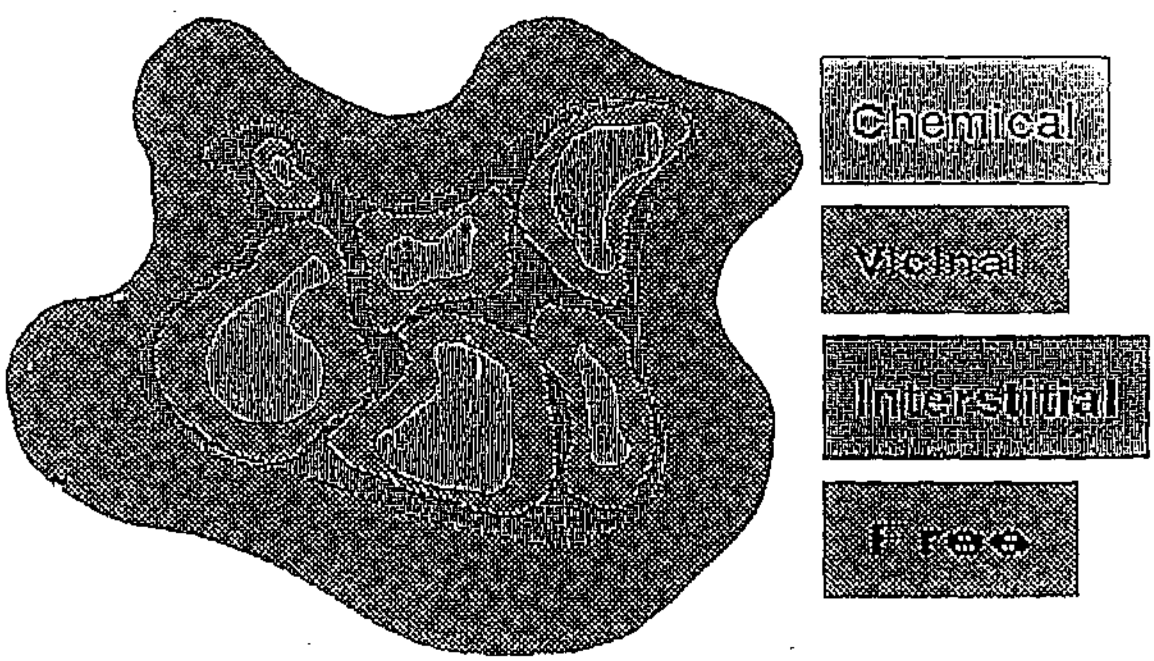


Figure 1 : Water distribution in sludge floc

There is sufficient evidence to say, that the relative quantitative magnitude of different water fractions determines the water retention characteristics of sludges and their relation to the performance of the dewatering system (Smollen 1988, Tsang and Vesilind,1990).

2.2. Occurrence of sludge liquids in electrical double layer

It is most important to investigate and interpret the physical and chemical phenomena that occur on the surface of sludge particle which is a part of a sludge flock. The prime characteristic of sludge particles is their large surface area. This provides not only highly chemically active surface area but also allows water to be held by adsorption.

Sludge particles are negatively charged. This charge is acquired by preferential adsorption of ions (counterions) from the solution. The combined system of the surface charge on the particle and the corresponding counterion charge in solution is known as the electrical double layer (Fig 2). It consists of a strongly attracted layer known as Helmholtz liquid and a diffused layer known as Smoluchowski liquid. According to the classification proposed by Dobosz (1980), sludge liquids fall into three groups: (1) Newtonian fluids, (2) Smoluchowski liquids, and (3) Helmholtz liquids. Occurrence of structured water in adsorption electrical double layer, known as Helmholtz liquids, is well documented (Johnson et al.,1966). This water can be identified with a vicinal water fraction, while part of a mobile diffusion double layer of Smoluchowski liquid, corresponds to an interstitial water fraction.

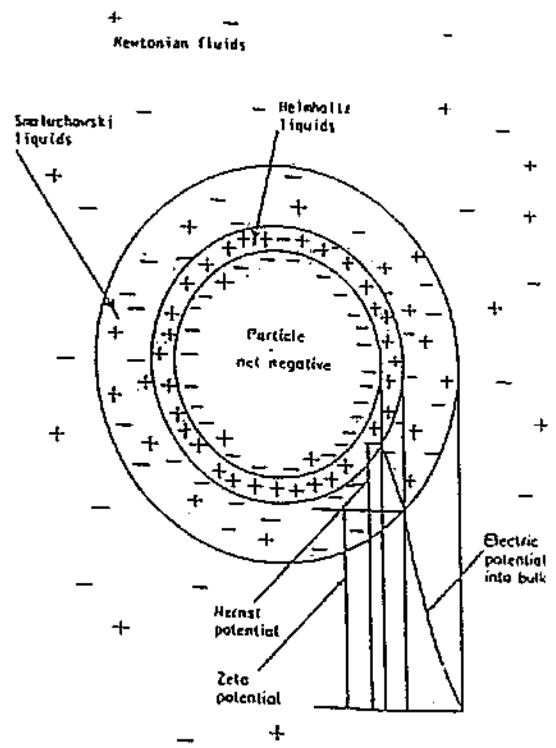


Figure 2 : Sludge-particle liquid electric double layer

The "thickness"of the diffuse layer is a very important parameter in determining the extent of interaction between charged colloidal particles. Different solutions will have different diffuse layer thickness. Thus, in distilled water the diffuse layer of counterions around a colloidal particle would have a thickness of about one micron, whereas in sea water the counterion charge would be confined to a region only a few Angstrom units thick (1Å = nm)(Gregory,1983). In biological sludges, which are generally characterised by low ionic strength, the diffuse layer can extend out to as much as 20 Å.

The magnitude of the particle charge derived from the compact layer is called zeta (ζ) potential and represents the repelling force of the particle, opposite to attractive van der Waals forces. Zeta (ζ) potential is interpreted in terms of the potential at the boundary between the fixed and the mobile parts of the double layer.

2.3. Electroosmosis (EO)

The development of the theory of the electric double layer dates from 1879 and the work of Helmholtz, who postulated that formation of such a layer was of general occurrence at a phase boundary. He related mathematically the velocity of electroosmotic flow to charge separation in the double layer; the flow was shown to depend on an "electrokinetic potential" that corresponds to the potential drop across the layer of charge contained in the moving liquid (Sennett and Olivier,1964).

Electrokinetic phenomenon such as EO arises when applied voltage causes a relative displacement of the charged solids surfaces, since at least part of the diffuse layer charge is mobile and can move with the liquid. An applied voltage causes a relative displacement of the charged layers; the liquid being free to move thus flows in a direction dependent on the charge it carries.

In the classical studies of early research (about 1850) mass flow rate during electroosmosis was found to be independent of porous diaphragm immersed in water or other liquid. Porous diaphragm essentially consists of a mass of fine capillaries. If the pores in particles of sludge have minute capillary structures, liquid flow will continue as long as a potential difference is maintained, independent of the capillary dimension.

Transport of electric charge due to relative motion between the surface of a solid and a fluid is used for measuring the ζ - potential of a sample surface. When a solid is fixed and a pressure is applied to force liquid to flow along its surface, the liquid flows carrying the ions off the sample surface. Consequently microscopic flow of electric charge occurs leading to the generation of an electric potential difference, E, between electrodes placed perpendicular to the direction of flow. The amount of electric charge moving is proportional to the flow rate of the liquid. Because this flow rate is proportional to the pressure drop, P (Poisseuille's equation), then under laminar flow conditions the relation between E and P can be expressed by the Helmholtz-Smoluchowski equation:

$$E = P \xi e / 4\pi \eta \lambda \qquad (1)$$

where e is the dielectric constant of the medium and η is the coefficient of viscosity. The ξ-potential can be calculated from equation 1, provided that the values of the slope of the E-P curve and the specific conductivity of the liquid, λ, can be obtained (Igarashi & Nishizawa, 1992).

It is considered that a continuous electroosmotic dewatering can be described most accurately by the following equation (Martynenko et al, 1991):

$$Q = Q_o (1\text{-}\exp(-k_o Vt/L^2)) \qquad (2)$$

where Q is a volume of filtrate removed by electroosmosis, Q_o initial volume of sludge to be dewatered, V - voltage, t - time of electroosmosis, k_o electroosmotic coefficient and L - distance between electrodes.

The energy requirements, E_w, for electroosmotic dewatering, according to Gray and Mitchell (1967), can be calculated from the following equation:

$$E_w = V/k_o R \qquad (3)$$

where V-voltage, k_o - electroosmotic coefficient and R - specific electrical resistance.

2.4. Liquid fractions in relation to methods of sludge dewatering

Sludge dewatering enhanced by EO is caused by application of an external electric field and theoretically can be considered independent of the capillary structure. Therefore electroosmotic dewatering is particularly effective for fine-particle and gelatinous sludges which are difficult to dewater by conventional dewatering methods. This statement is supported by the extensive theoretical and practical research on electroosmotic dewatering, carried out relatively recently by Japanese researchers (Yukawa and Yoshida,1986, Yoshida and Yukawa, 1988, Yoshida and Yukawa,1992).

Study on quantification of moisture content using drying curve analysis were undertaken in order to relate the different categories of water to cake moisture content, after mechanical dewatering (Smollen 1986,1988,1990). Tsang and Vesilind (1990) performed similar drying studies and concluded that dewatering processes can only remove part of the free and interstitial moisture - surface and bound moisture are not affected. Part of the free and interstitial moisture remain within the sludge cake, which can be considered as an inherent inefficiency of the dewatering process. Robinson and Knocke (1992) used drying and dilatometric techniques for assessing water distribution in sludge cake, after mechanical dewatering. They also concluded that most of the water remaining after dewatering is free or interstitial in nature, water that is not directly bound to the particle surface.

The most recent study by Vesilind (1992) postulates that vicinal water, consisting of ordered and layered water molecules on the surface of submerged solids, cannot be removed mechanically. Further, he states, that polymers will only influence the interstitial water and will make it possible for the bulk and part of the interstitial water to be separated by mechanical means. A similar point of view was expressed by Smollen (1988, 1990).

An attempt is made to illustrate graphically in Fig 3 the occurrence of liquid in an electrical double layer in relation to a possible water removal method. It is shown that mechanical dewatering removes bulk water and only a part of the diffusion layer, while electroosmotic dewatering extends its boundaries much further into diffusion layer, which we identified as interstitial water fraction. Only thermal drying is shown to remove the remaining physically and chemically strongly bonded water. This is a simplified representation of water removal methods and there may be means of vicinal (adsorbed) water removal by some chemical changes of sludge particle surfaces which is not a subject concerning this study.

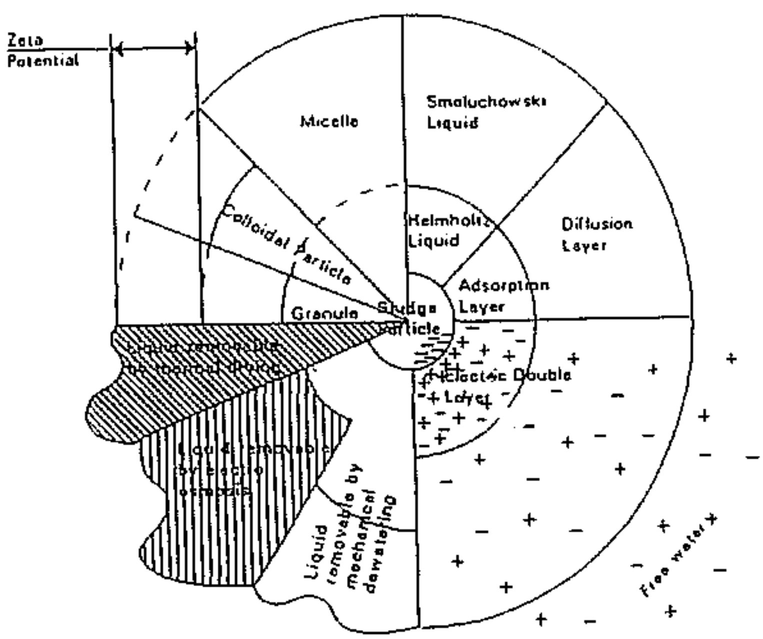


Figure 3 : Sludge-liquid in electric double layer in relation to the moisture removal methods

3. EXPERIMENTAL INVESTIGATION

Twenty two organic (municipal) and inorganic (waterworks and industries) sludge samples were investigated. Sludge details are illustrated in Table 1 in which numbers assigned to each sludge sample are given. List of sludge numbers is given on page (xi).

3.1 Preparation of samples

A representative sludge sample is required for sludge to be characterised by laboratory testing. Shipment or storage of organic sludges can affect sludge properties and give erroneous sludge characterisation data. As much as possible laboratory tests should be performed on fresh sludge samples. When necessary, storage at +4°C is allowed because it was verified that analytical parameters of the sludge samples stored at +4°C remained almost constant up to 30 to 40 hours, from the time of collection (Tiravanti et al 1985).

If samples are taken from a tank, the entire contents should first be well mixed. Extensive agitation of sludge changes certain physical characteristics by damaging floc. The mixing intensity should be gentle and mixing duration should not be excessive. From large tanks numerous samples should be taken in different locations and combined to provide a representative sample.

Before analysing, the entire sample should be mixed well in an appropriate manner. For measurements of parameters dealing with flock structure such as filtration, centrifugation and gravity thickening, gentle mixing is required. This can be achieved by pouring the entire sample carefully from one container to another.

TABLE 1 : SLUDGE DETAILS

Source of sludge sample	Treatment process	Sludge sample no.	Process parameters		Dewaterability	
			R_s	R_h	SRF	CST
			(d)	(d)	($\times 10^{12}$m.kg^{-1}	(s)
Organic sludge						
Athlone	WAS (1), AD	1, 2	12 - 15	40	110, 230	50, 300
Atlantis	WAS (1)	3a, 3b	25 - 30	-	8	6
Bellville	WAS (1)	4a, 4b	14	-	9	7
Borchard's Quarry	WAS (1) , AeD	5, 6	12 - 15	25 - 30	7, 11	8,12
Cape Flats	WAS (2), AD	7, 8	12 - 15	10	350, 580	130, 420
Mitchell's Plain	WAS (1), AD	9, 10	15	20	98, 720	80, 375
Scottsdene	WAS (1)	11	30 - 40	-	8	9
Stellenbosch	BF & WAS (1)	12	20	-	13	10
Package plant	WAS (2)	13	-	-	15	10
Milnerton	Z	18	-	-	0,2	12
Kraaifontein	AD (1)	19	-	60	38	130
Centrifuged cake	WAS (1)	20	-	-	-	-
Inorganic Sludge						
Blackheath	Waterworks (alum sludge)	14	-	-	80	36,0
Steenbras	Waterworks (alum sludge)	15	-	-	0,1	6,5
Voëlvlei	Waterworks (iron sludge)	16	-	-	44	30,0
Sulphur waste	Industrial ($BaSO_4$)	17	-	-	-	-

4. LABORATORY INVESTIGATION OF ELECTROOSMOTIC DEWATERING

4.1 Apparatus

A schematic diagram of the electroosmotic apparatus used in laboratory investigation is shown in Fig 4. The lower electrode (3) placed at the bottom of the perspex funnel consists of perforated aluminium plate covered by filter paper. The upper electrode was made of carbonic material to render it corrosion resistant. The polarity of both electrodes is determined according to the negative charge of sludge particles - upper anode and lower cathode. This facilitates the movement of water downwards, and sludge particles upwards.

Contact between the upper electrode and the sludge bed is maintained by manual adjustment. Care is taken not to compress the sludge by the upper electrode in order to avoid an additional compression effect.

Electric field under a constant voltage is applied to the sludge bed by a regulated DC power supply and electric current is recorded automatically.

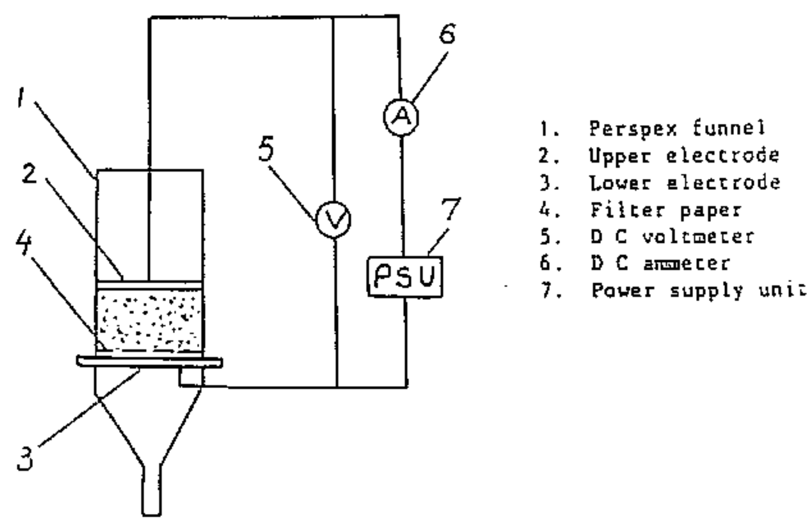


Figure 4 : Laboratory electroosmotic apparatus

4.2 Experimental procedure

About 200 mL of sludge was added to the electroosmotic apparatus. For comparative purposes tests at different voltages of 5,10,15 and 20 V were carried out. The test was discontinued when a number of consequent readings of collected filtrate were the same.

In order to compare the electroosmotic with conventional dewatering methods, the following laboratory tests were conducted:

1. Draining experiment where sludge samples were subjected to gravity dewatering until such time that no more moisture could be removed.

2. Filtration at 3 atmospheres for 30 minutes in a laboratory pressure cell.

3. Laboratory centrifugation at 3960G, for duration of 5 minutes.

Percentage of cake solids concentration (on wet basis) was determined on sludge cake produced by all four dewatering methods, i.e. gravity drainage for 24 h, filtration, centrifugation and electroosmosis.

4.3. Results and discussion

4.3.1. Electroosmotic dewatering at different voltages

The electroosmotic dewatering results shown in Table 2 illustrate three different type of sludges which are subjected to the laboratory test at different voltages. At each voltage the following parameters are given: duration of the test (h), current efficiencies (L/Ah), energy requirements (Wh/L) and final cake solids concentration (wt.%). The L/Ah and Wh/L values are calculated from the cumulated volume of water removed during the electroosmotic dewatering and the currents at each voltage.

Between 0 and 10 V dewatering was slow and limited. An appreciable degree of dewatering was achieved between 10 and 20 V. It was observed that current efficiency decreased gradually because the electric resistance of the dewatered sludge increased as dewatering proceeded, and the dewatered sludge volume was reduced to a terminal value (Fig 5).

Since watt-hours are the product of amp-hours and voltage, it follows that even when the L/Ah is independent of voltage, the Wh/L value is directly proportional to the voltage. This is illustrated in Table 2 where an increase in voltage is associated with an increase in energy requirements.

In order to minimise electrical energy consumption, while maintaining reasonable dewatering, it is advisable to use a lower voltage. It is shown in Table 2 that in order to achieve the No 1 (Table 1) activated DAF sludge cake solids concentration of 15,6% at 15 V, the energy requirements are almost half of that which is required to achieve 19,7 % at 20V. Even more explicit is the example with No 11 (Table 1) anaerobically digested sludge, shown in Table 2 and Fig 5(c). Sludge cake of 13,4 % was achieved at 15V, while 20V resulted in low 9,5% cake solids, with twice as high energy use.

The duration of the test, until the filtrate flow stops, decreases with increase in applied voltage and is influenced very significantly by the type of sludge, i.e. the fastest appears to be activated sludge, thickened by gravity, taking only 1,2 hour at 15V with resulting 13,6% cake solids while No1 (Table 1) activated from DAF took 4,5 hours to be dewatered to 15,6% and anaerobically digested 5 hours, to reach 13,4 %.

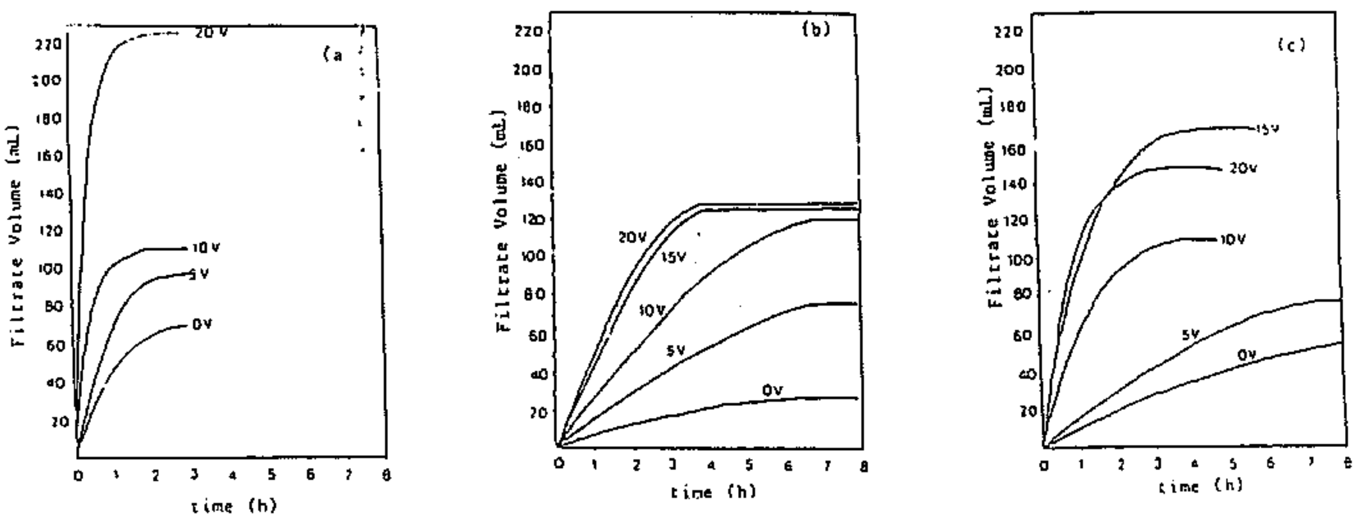


Figure 5 : Relationship between filtrate volume and time at different voltages
(a) Sludge No 13
(b) Sludge No 1 (Table 1)
(c) Sludge No 11

TABLE 2 : LABORATORY EXPERIMENTAL RESULTS FROM ELECTROOSMOTIC DEWATERING AT DIFFERENT VOLTAGES (no polyelectrolyte)

* Type of sludge * No of sample	Initial solids (%)	Voltage (V)	Duration of electroosmotic dewatering (h)	Current efficiencies (L/Ah)	Energy requirements (Wh/L)	Final cake solids (%)
WAS (1)	2,4	0	2,0	-	-	5,9
		5	1,7	0,34	147	9,6
13		10	1,2	0,24	420	13,6
		20	1,3	0,16	1260	15,7
WAS (1)	4,4	0	8,0	-	-	6,5
		5	6,5	0,14	35	8,0
1		10	7,0	0,03	367	13,2
		15	4,5	0,02	678	15,6
		20	4,2	0,02	1112	19,7
AD	1,1	0	8,0	-	-	1,4
		5	6,0	0,5	111	1,8
11		10	5,5	0,4	275	8,7
		15	5,0	0,3	484	13,4
		20	3,5	0,2	1076	9,5

* Table 1

4.3.2. *Electroosmotic dewatering in relation to other dewatering methods*

In Table 3 results from electroosmotic tests are compared with other conventional methods of dewatering, i.e. drainage, filtration and centrifugation. In most cases results from EO are superior to those produced by other methods. It appears that EO works well with very difficult to dewater anaerobically digested (be it primary or a mixture of primary) and waste activated sludges. An example in Table 3 illustrates that No10 (Table 1) anaerobic sludge sample, with initial cake solids concentration of 1,9%, reached the following final cake solids: after drainage - 2.3%; after filtration - 2.6%; after centrifugation - 7.6% and after electroosmosis - 20.2%.

In practice, the 20.2% of cake solids concentration is hardly ever achieved by any mechanical equipment, even with the aid of chemical conditioners. This is due to the large amounts of sludge moisture, bound in the electric double layer, which cannot be removed by mechanical methods.

White solid substances were deposited, in a form of layer, on the surface of the aluminium electrode. This is known as polarization and cataphoresis, which pollute electrodes and reduce electric power efficiency. It is expected that only the laboratory scale EO experiment can be siginificantly influenced by the polarization phenomenon.

TABLE 3 : COMPARISON OF CAKE SOLIDS CONCENTRATION AFTER ELECTROOSMOTIC AND TRADITIONAL DEWATERING LABORATORY TESTS (no polyelectrolyte)

* Type of sludge	* Sludge sample No	Initial solids concentration (%)	Final cake solids concentration (%)			
			Drainage	Filtration	Centrifugation	Electroosmosis
WAS	12	-	3,7	-	-	19,4
	11	3,9	3,7	-	-	16,0
	5	1,4	4,5	17,0	3,2	15,9
	4a	2,3	5,9	25,0	12,8	15,7
	4b	2,0	2,6	9,5	6,9	9,3
	3b	0,8	4,4	19,0	6,4	4,9
	12	3,4	14,0	30,0	14,0	25,0
	3a	2,5	3,7	29,0	8,9	11,7
	3b	0,7	3,0	19,0	7,1	7,1
	4a	1,3	3,4	23,7	11,7	10,8
WAS	1	3,4	4,7	10,0	7,2	17,4
	7	1,8	4,1	24,5	10,6	10,4
	1	3,8	4,9	9,0	8,9	17,2
	9	3,8	7,2	9,7	8,7	13,3
	5	4,4	7,3	6,5	7,7	18,2
AD	10	3,2	3,5	10,8	10,5	18,0
	8	6,5	5,8	5,8	5,9	21,0
	10	1,9	2,3	2,6	7,6	20,2
	2	7,6	10,5	19,6	17,1	22,5

* Table 1

5. STUDY OF SLUDGE DEWATERING USING SINGLE STAGE ELECTROOSMOTIC FILTER-BELT SCALE MODEL

Based on the laboratory results it was found that the electroosmotic phenomenon facilitates dewatering of troublesome municipal sludges. It was however realised that the laboratory conditions are not fully comparable with practical application. A scale model, which incorporates EO into filter-belt press was partly build, based on the idea which was patented (SA patent 91/0538). The scale model, in it's abbreviated form was run, while awaiting it's further development. The initial runs not only provide information for the next phase of development of the model but also provide valuable results which give insights into the difficult problem of sludge dewatering (Smollen and Kafaar 1993).

5.1. The single stage scale model

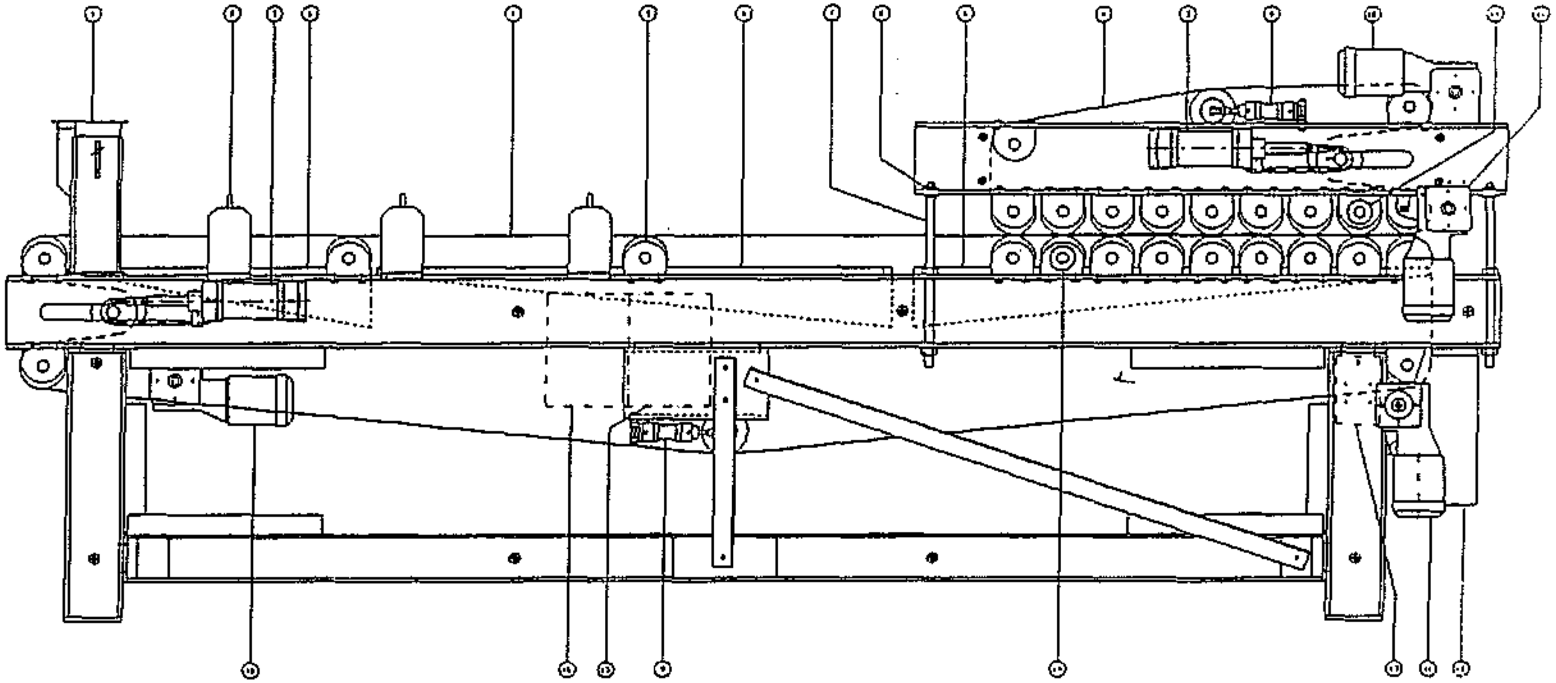
In Figure 6, the scale model general arrangement is illustrated. Due to financial constrains only one stage of the patented two stage concept was built. The plant's dimensions are : length - 3.650 meter, width - 0.500 meter and height - 1.500 meter. It consists of a feed box, horizontal belt gravity dewatering section and electroosmotic section, where sludge is squeezed between two belts. Belts are made of electrically conductive material. The anode and cathode electrodes, which are the upper and lower belt respectively, are connected to a DC power supply. The sludge is sandwiched between the opposite electrodes and due to electroosmotic action, the water is caused to move to the cathode, and negatively charged sludge particles - to the anode electrode.

The conditioned sludge is fed into the feed box and then onto the gravity drainage belt. Belt support for the gravity drainage section is provided by idler rollers. To achieve effective sludge distribution over the conveyer belt, three rows of ploughs were installed.

The gap between the two belts in the electroosmotic section can be adjusted in order to exert mechanical pressure to achieve more effective sludge dewatering. One of the most important mechanisms to decrease or increase pressure throughout the entire EO section is the belt tension control device. Pneumatic controls for belt tensioning and tracking (steering) were installed. Compressed air is delivered by a compressor.

Cleaning of the cathode electrode is essential to remove a deposit (calcium hydroxide) formed during electroosmotic dewatering. For this purpose rotating belt brushes and belt wash water spray nozzles are provided.

The filtrate which is discharged during gravity drainage and electroosmotic dewatering was collected by three drip trays and sludge cake after electroosmotic section is separated from the belt by means of rotating brush.The strength of the press frame is of paramount importance and consists of bolted channel beams corrosion protected by primer and paint.



1	Feed Box	5	Idling Roller	9	Belt Steering Assy	13	Belt Wash Station
2	Plough Assembly	6	Drip Tray	10	Belt Drive Unit	14	DC Brush Unit
3	Belt Tensioning Assy	7	Electric Insulation	11	Brush Motor	15	DC Power Supply
4	Belt	8	Carriage Mounting Assy	12	Collecting Box	16	Belt Speed Controller

Figure 6 : Single stage dewatering scale model (side view)

5.2 Experimental procedure

The scale model experimental runs were performed on activated and anaerobically digested sludges collected from seven different wastewater treatment works in Western Cape area. Inorganic sludges were also investigated i.e. samples from three different waterworks were obtained (two alum and one ferric sulphate) and one sample of sulphur waste (barium sulphate) (Table 1).

The experiments were carried out on sludges with and without addition of polyelectrolyte. The addition of polyelectrolyte was calculated on the basis of mass of polyelectrolyte per unit mass of dry solids in the sludge and was expressed in kg per ton of dry solids (kg/tds). Minimal dosage of a polyelectrolyte (up to 2 kg/tds) was maintained by visual assessment of the first signs of sludge flocculation, which indicated the minimum amount of polymer required. For comparative purposes relatively high dosages of polyelectrolyte (3 to 6,5 kg/tds) were also used. After addition of polyelectrolyte, the entire sample was mixed and then left for a period of time, sufficient for the sludge to settle. The separated water was subsequently decanted and the settled sludge was used for further dewatering by the pilot plant.

The scale model tests were run not on a continuous basis but in a batch mode. Each sludge sample was subjected to two runs: the first control run, without EO and the second run - with electroosmotic action. In order to simulate the patented stage configuration of the pilot plant, sludge cake obtained after the first full run was returned and re-entered into the passage between the two belts, for a second time. Thus the experimental run consisted of:

- 1st stage of dewatering : gravity and belt pressing section
(with and without electroosmosis)

- 2nd stage of dewatering : only belt pressing section
(with and without electroosmosis)

The sludge residence time in the gravity section was 4 min and in the section between belts, 10 min, thus the total dewatering time was approximately 14 min.

Determination of the total solids concentration was carried out on the following sludge samples:

* initial sludge solids concentration
* cake solids after 1st stage of dewatering (no electroosmosis)
* cake solids after 2nd stage of dewatering (no electroosmosis)
* cake solids after 1st stage of dewatering (with electroosmosis)
* cake solids after 2nd stage of dewatering (with electroosmosis)

The electroosmotic runs were carried out at different voltages i.e. 5V, 10V, 15V and 20V. At each voltage current efficiency and energy requirements were calculated. The L/Ah (litres of water removed per ampere-hour) and Wh/L (watt-hours per litre of water removed) were calculated at each voltage from the cumulated volume of water removed and the recorded current.

5.3 Results and discussion

The scale model experimental results are illustrated in Tables 4,5,6 and 7. The first three tables correspond to results concerned with biological sludges and in Table 7 - results are given from chemical sludges.

In order to obtain as much information as possible on the response of different type of sludges to scale model electroosmotic dewatering, batch (not continuous) mode of operation was used.

Electroosmotic dewatering is inherently a direct-current process and can be carried out under conditions of either constant electric current or constant voltage.

5.3.1 Batch dewatering at constant voltage

The scale model experimental runs were carried out at constant voltage and the following observations were made:

The amperage values increase when wet sludges enters the electroosmotic section, and decreases as dewatering progresses. The electrical current decreases with time because of the increase in electrical resistance caused by decrease in the water content.

At the end of the batch dewatering, the sludge layer, near the upper electrode, appears to be completely dewatered (Fig 7). The sludge cake separates into two layers:

(1) the dewatered upper layer of different, much lighter colour,
(2) the darker in colour, underdewatered lower layer

No significant blinding of the filter-belt material was observed. As sludges exhibit a net negative charge when an electric current is applied, charged particles are directed away from the filter medium significantly reducing filter media blinding.

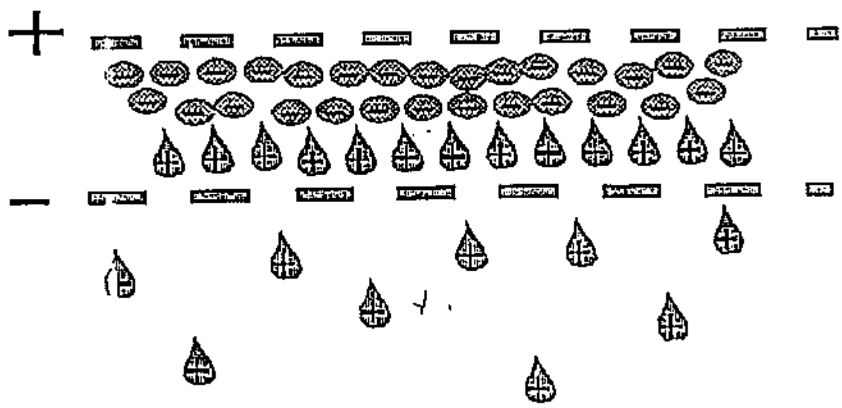


Figure 7 : Sludge cake stratification during electroosmosis

There is an optimum operating condition with regard to dewatering rate and electrical power consumption, also predicted by preceding laboratory investigation. A higher voltaage is not necessarily effective for increase in deatering rate. It is shown in Table 5 that activated sludge from Borcherd's Quarry reached cake solids concentration of 12,7 % at 10 V, after the 1st stage of dewatering, using only 193 Wh/L. When it was subjected to the 2nd stage of dewatering at 20 V, the energy requirement was almost six times higher than in the 1st stage and only slight cake solids increase, to 14,7 %, was achieved. Similar case is shown in Table 7. Inorganic sludge ($BaSO_4$) after the first stage of dewatering achieved 72 % at 5 V, using only 144 Wh/L. After the second stage, cake solids reached only 74 %, using an incredible 2435 Wh/L.

The energy requirements increase with increase in voltage, in some cases reaching very high values. It appears that dewatering of anaerobically digested sludges require more energy than that of activated sludges. Flocs of activated sludge are well defined, with much smaller surface area than that of digested sludge, which is characterised by high dispersion of small particles, thus much bigger surface area. This tends to support the assumption that more liquid is held within electric double layer on anaerobically digested than on activated sludge particles. This results in a higher energy requirement for removal of a water bound to the surface of anaerobically digested than to activated sludge particles.

Low values of current efficiencies, in the range of 0,18 to 0,01 L/Ah, were observed, decreasing with increasing voltage. Decrease in current efficiency was also observed while proceeding with electroosmotic dewatering under constant voltage, mainly due to increased electrical resistance. Current intensity is dictated by voltage and electrical conductivity of the liquid phase. On the contrary, when it is low, high applied voltage is needed. More research is needed to find means for improvement of current efficiency in electroosmotic sludge dewatering.

During the scale model experimental trials no white solid substances, observed during laboratory investigation (Chapter 4.3.2), were deposited on the surface of the electrodes (belts).

5.3.2 *Effect of addition of polyelectrolyte*

Addition of polyelectrolyte was necessary in order to improve solids-liquid separation in the gravity section of the scale model. An insignifcent improvement in cake solids concentration, due to polyelectrolyte addition, was obtained after electroosmotic dewatering of activated sludges. No 11 (Table 1) WAS from Scottsdene at 5 V reached 10,3 % without polyelectrolyte (Table 4), 9,1 % with low polyelectrolyte dosage (Table 5), and 10,6 % with high dosage (Table 6). It appears that very difficult to dewater anaerobically digested sludges from Cape Flats and Mitchell's Plain (No 8 & 10 in Table 1) are positively affected by the polyelectrolyte addition, reaching 16,3 % and 22,6 % cake solids respectively (Table 6).

Effect of addition of polyelectrolyte appears to depend on the type of sludge and its electrical characteristics. The electrical characteristic of the sludge depends on physical and chemical phenomena that occur at the interface of the electric double layer. After addition of polyeleectrolyte, the amount of electrical current is proportional to the remaining charge. Addition of polyeleectrolyte provides an opposite excess charge in the liquid phase, to balance the surface charge of the sludge particle. This improves the efficiency of the applied voltage gradient which causes the electroosmotic flow. thus, the highest energy consumption was shown by sludge without addition of polyelectrolyte (Table 4), and decreases with increased polyelectrolyte dosage (Tables 5 & 6), i.e. WAS from Scottsdene at 15 V, after 1st stage of dewatering, showed 458 Wh/L (no polyelectrolyte), 389 Wh/L (low dosage) and 103 Wh/L (high dosage).

5.3.3 *Effect of initial solids concentration*

Initial sludge solids concentration effects the final cake solids concentration. In Fig 8 it is shown that the activated sludge thickened by DAF reaches higher final cake solids concentration with an increase in initial solids, i.e. initial solids concentration of 1,8 % corresponds to 11% cake solids, while 4,3 %initial solids reaches 18,3 % final cake solids concentration. Therefore, sludge have to be prethickened to a highest possible solids concentration, prior to subjecting it to EO dewatering.

Because there is a large installed capacity of centrifuges and vacuum filters, EO filter-belt press can be used to reduce moisture content of previously formed sludge cake.

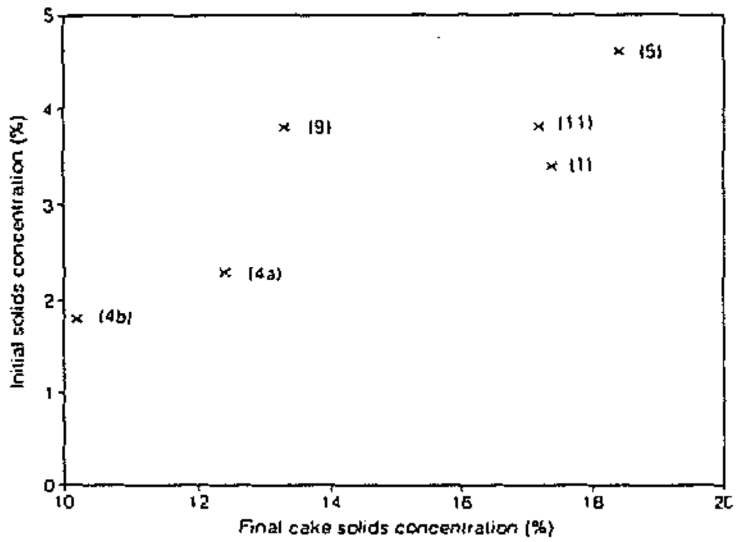


Figure 8 : Initial solids versus final cake solids concentration
( ) - sludge sample number

TABLE 4 : EXPERIMENTAL RESULTS FROM ELECTROOSMOTIC SCALE MODEL (no polyelectrolyte)

* Sludge sample		1st stage of dewatering					2nd stage of dewatering				
		0V	5V	10V	15V	20V	0V	5V	10V	15V	20V
WAS (1) - Scottsdene	% solids	4,4	6,3	7,1	10,3	9,4	5,3	9,4	10,6	13,2	15,0
* No 11	L/Ah	-	0,11	0,03	0,03	0,07	-	0,08	0,03	0,04	0,04
** c = 1,8 %	Wh/L	-	44	354	458	664	-	59	368	413	522
WAS (1) - Mitchell's Plain	% solids	5,7	-	6,3	-	8,1	7,0	-	8,7	-	9,1
* No 9	L/Ah	-	-	0,04	-	0,06	-	-	0,21	-	0,01
** c = 4,3 %	Wh/L	-	-	250	-	356	-	-	459	-	1603
AD - Cape Flats	% solids	-	-	-	6,1	-	6,1	-	-	-	10,0
* No 8	L/Ah	-	-	-	0,02	-	-	-	-	-	0,015
** c = 1,7 %	Wh/L	-	-	-	1000	-	-	-	-	-	1326

* Table 1
** c - initial solids concentration

TABLE 5 : EXPERIMENTAL RESULTS FROM ELECTROOSMOTIC SCALE MODEL (WITH LOW POLYELECTROLYTE DOSAGES: 0,5 to 2,0 kg/Tds)

* Sludge sample		1st stage of dewatering					2nd stage of dewatering				
		0V	5V	10V	15V	20V	0V	5V	10V	15V	20V
WAS (1) - Borcherd's Quarry	% solids	7,8	-	12,7	-	-	9,8	-	-	-	14,7
* No 5	L/Ah	-	-	0,08	-	-	-	-	-	-	0,01
** c = 1,8 %	Wh/L	-	-	193	-	-	-	-	-	-	1130
AeD - Borcherd's Quarry	% solids	7,3	-	-	8,1	-	9,7	-	-	13,6	-
* No 6	L/Ah	-	-	-	0,06	-	-	-	-	0,02	-
** c = 2,3 %	Wh/L	-	-	-	258	-	-	-	-	708	-
WAS (1) - Scottsdene	% solids	5,4	7,2	8,6	9,2	10,0	6,3	9,1	12,1	12,2	12,2
* No 7	L/Ah	-	0.08	0,04	0,04	0,06	-	0,08	0,04	0,03	0,05
** c = 1,3 %	Wh/L	-	60	249	389	311	-	60	226	480	394
WAS (1) - Mitchell's Plain	% solids	5,6	-	6,0	-	6,8	7,9	-	8,3	-	10,0
* No 9	L/Ah	-	-	0,07	-	0,03	-	-	0,02	-	0,03
** c = 3,6 %	Wh/L	-	-	145	-	597	-	-	413	-	565
AD - Cape Flats	% solids	15,8	-	16,0	16,3	19,4	20,0	-	21,8	24,5	28,1
* No 8	L/Ah	-	-	0,05	0,06	0,04	-	-	0,04	0,09	0,02
** c = 4,0 %	Wh/L	-	-	223	259	577	-	-	272	170	1215

* Table 1
** c - initial solids concentration

TABLE 6 : EXPERIMENTAL RESULTS FROM ELECTROOSMOTIC SCALE MODEL (with high polyelectrolyte dosages: 3,0 to 6,5 kg/Tds)

* Sludge sample		1st stage of dewatering					2nd stage of dewatering				
		0V	5V	10V	15V	20V	0V	5V	10V	15V	20V
WAS - Package Plant	% solids	-	-	-	9,6	-	-	-	-	17,2	-
* No 13	L/Ah	-	-	-	0,08	-	-	-	-	0,13	-
** c = 1,3 %	Wh/L	-	-	-	194	-	-	-	-	116	-
WAS - Stellenbosch	% solids	7,9	8,2	8,9	9,8	10,0	9,6	11,0	11,9	13,5	13,8
* No 12	L/Ah	-	0,10	0,08	0,06	0,04	-	0,10	0,06	0,06	0,03
** c = 1,3 %	Wh/L	-	47	117	267	500	-	50	161	276	599
WAS - Scottsdene	% solids	6,8	7,6	-	9,2	-	9,5	10,6	-	14,9	-
* No 11	L/Ah	-	0,15	-	0,15	-	-	0,09	-	0,07	-
** c = 1,1 %	Wh/L	-	33	-	103	-	-	54	-	202	-
WAS - Cape Flats	% solids	8,6	-	-	9,0	-	10,4	-	-	14,6	-
* No 7	L/Ah	-	-	-	0,06	-	-	-	-	0,06	-
** c = 2,3 %	Wh/L	-	-	-	268	-	-	-	-	294	-
AD - Cape Flats	% solids	7,3	-	8,5	7,1	8,2	8,1	-	11,6	12,8	16,3
* No 8	L/Ah	-	-	0,04	0,06	0,05	-	-	0,08	0,06	0,06
** c = 1,9 %	Wh/L	-	-	239	262	361	-	-	125	259	336
AD - Mitchells Plain	% solids	6,0	10,0	12,5	11,7	13,6	11,3	13,2	16,8	19,0	22,6
* No 10	L/Ah	-	0,09	0,05	0,03	0,03	-	0,01	0,02	0,03	0,04
** c = 1,5 %	Wh/L	-	52	184	475	698	-	608	604	566	462

* Table 1
** c = initial solids concentration

TABLE 7 : EXPERIMENTAL RESULTS FROM ELECTROOSMOTIC SCALE MODEL (inorganic sludge with high polyelectrolyte dosage: 0,5 to 2,0 kg/Tds)

* Sludge sample		1st stage of dewatering					2nd stage of dewatering				
		0V	5V	10V	15V	20V	0V	5V	10V	15V	20V
Chemical sludge	% solids	-	72	-	-	-	-	-	-	-	74,0
* No 17	L/Ah	-	0,04	-	-	-	-	-	-	-	0,002
** c = 41,0 %	Wh/L	-	144	-	-	-	-	-	-	-	2435
Blackheath	% solids	-	-	-	6,1	-	-	-	-	10,0	-
* No 14	L/Ah	-	-	-	0,18	-	-	-	-	0,12	-
** c = 0,3 %	Wh/L	-	-	-	81	-	-	-	-	120	-
Voëlvlei	% solids	9,9	-	-	-	21,6	16,2	-	-	-	31,5
* No 16	L/Ah	-	-	-	-	0,15	-	-	-	-	0,03
** c = 1,4 %	Wh/L	-	-	-	-	134	-	-	-	-	755
Steenbras	% solids	-	-	-	-	4,7	-	-	-	-	8,4
* No 15	L/Ah	-	-	-	-	0,5	-	-	-	-	0,04
** c = 3,6 %	Wh/L	-	-	-	-	30	-	-	-	-	165

* Table 1
** c - initial solids concentration

6. INVESTIGATION OF SLUDGE DEWATERING USING THE DOUBLE STAGE ELECTROOSMOTIC FILTER-BELT SCALE MODEL

Due to financial constrains building of the scale model did not follow patented staged configuration. Partly built plant was subsequently developed to incorporate two stages of sludge dewatering.

6.1. Two stage dewatering model.

In Figure 9 two stage EO filter-belt scale model is illustrated. The additional pressure stage with belt snaking provides the possibility of converting it to the electroosmotic stage, equipped with an independent power supply. Figs 10 and 11 are photographs which illustrate side views of the plant with control box and filtrate collection points respectively.

During the experimental trials the S-path had to be adjusted to the same straight line as the existing electroosmotic stage. This is because a pressure exerted between two narrow, only 30cm width, snaking belts created lateral sludge loss. There were not sufficient funds and time during the course of the investigation to convert the additional stage to electroosmosis. This additional stage functioned purely as a mechanical sludge pre-thickening stage, prior to the existing electroosmotic stage.

Description of the experimental model is given in the preceding Chapter 5.1.

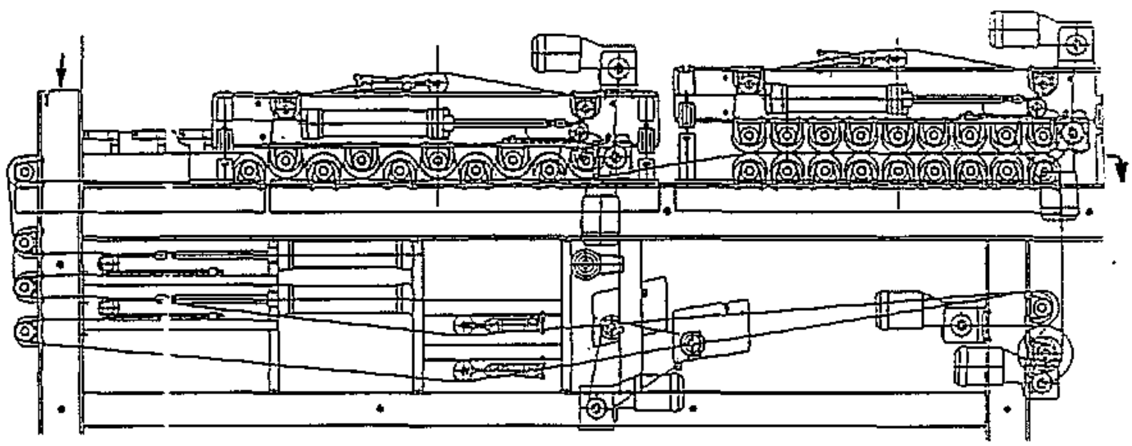


Figure 9 : Double stage dewatering scale model (side view)

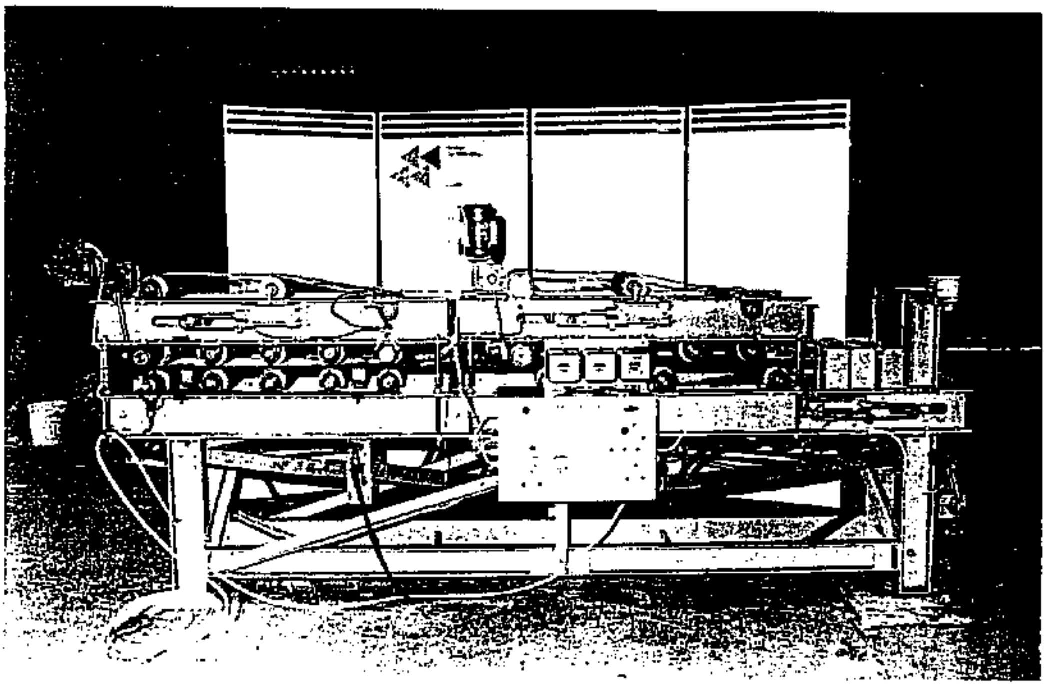


Figure 10 : Side view with electrical control box

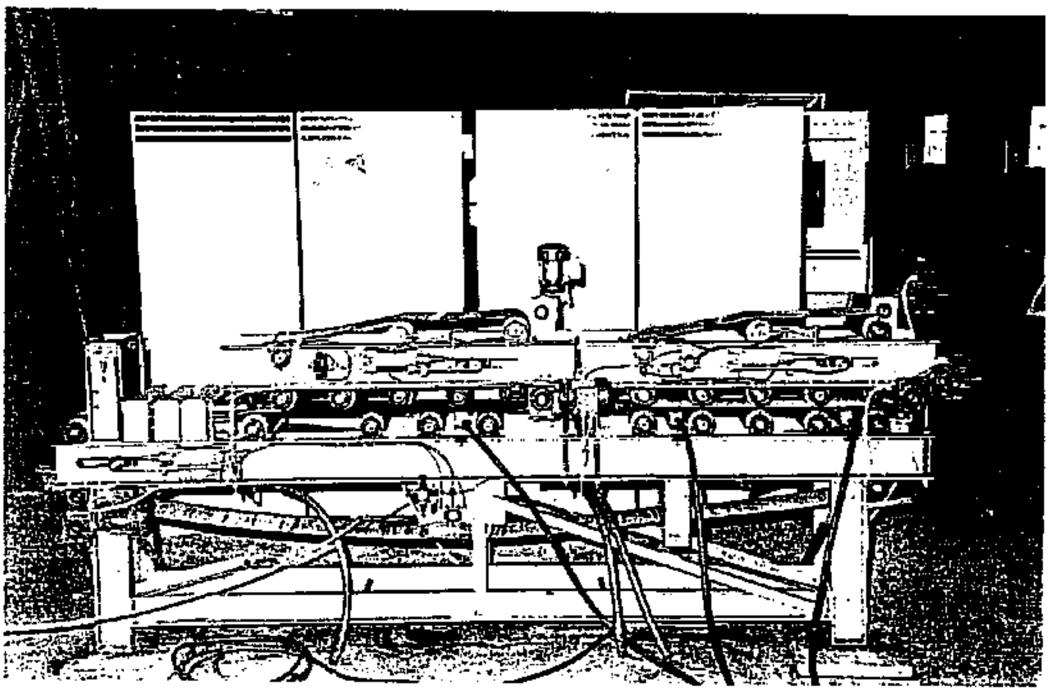


Figure 11 : Side view with filtrate collection points

6.2. Experimental procedure

Experimental trials were carried out on waste activated sludges, activated sludges thickened by DAF and anaerobically digested which were a mixture of primary and activated sludges. One sample of DAF sludge cake which was obtained after full-scale centrifugation was also subjected to the electroosmotic trial. The above sludge samples were obtained from the same sources as in the preceding one stage electroosmotic trials. Additionally two waterwork sludges were investigated. The sludge details are illustrated in Table 1.

Evaluation of performance of the electroosmotic belt-press model was carried out with regard to the following parameters:

(a) Two-stage dewatering
(b) Variable belt speed
(c) Variable voltage
(d) Variable gap between belts
(e) Use of polyelectrolyte
(f) Energy requirements
(g) Cake solids concentration
(h) Cake appearance
(i) Solids content in filtrate
(j) Mass and water balance
(k) Throughput

6.3. Results and Discussion

The results of the experimental trials carried out using the two stage dewatering model are illustrated in Tables 8,9,10,11 and 12.

Only one set of results of waterwork ferric sulphate sludge is included (Table 9). Alum sludge from the Steenbras Water Treatment Plant proved to be unable to form a sludge cake when passed between two running belts. This is due to non-fibrous dispersed sludge particle structure, specific for alum sludges.

6.3.1. Role of the additional mechanical stage

Mechanically assisted electroosmotic dewatering ensures more effective sludge dewatering because electrical energy is not wasted to remove water that can be removed by mechanical means. The belt conveyor installed ahead of electroosmotic section fulfils the role of sludge pre-thickener which beneficially influences not only the electric energy consumption but also final cake solids concentration. Higher initial solids result in higher final cake solids content (Chapter 5.3.3.).

6.3.2. Belt speed effect

Belt speed determines the retention time during which the dewatering process takes place. The time during which the sludge is passing between two belts (electrodes) decreases due to the faster movement of the belt, effectively decreasing the residence time. It is illustrated in Table 9 that low speed of 25mm/min resulted in higher cake solids content than that of 100mm/min.

6.3.3. Gap between belts in electroosmotic section.

The gap between the belts determines the cake thickness. At a given belt speed, increasing cake thickness increases throughput without decreasing the retention time.

The scale model tests were run at two different gaps between the belts i.e. 4 and 8 mm. The bigger gap (8mm) produced lower cake solids than the smaller (4mm) one (Table 9). In order to maintain a bigger gap between the electrodes, longer retention time (lower belt speed) has to be provided. However, fine-particle, non-fibrous sludges, such as waterworks sludges, cannot be successfully dewatered when gap between belts is too big. There are not enough solids for sludge cake to be formed.

6.3.4 Use of polyelectrolyte

The use of polyelectrolyte for EO dewatering is not necessary. However, low dosage of 1 to 2 kg per ton of dry solids was used in order to improve solids-liquid separation in the gravity and mechanical sections of the belt-press.

According to the investigation which was carried out using the partly built EO plant, addition of polyelectrolyte improves the efficiency of the applied voltage gradient, which causes deecrease in energy requirements (Chapter 5.3.2).

6.3.5 Energy requirements

During the laboratory study and single-stage (partly built) scale model investigation - the energy requirements appeared to be very high. This was because the energy calculation was based on the cumulative volume of filtrate recovered during the dewatering process, ignoring such factors as water lost to evaporation, water adhering to the apparatus (belt wetting) etc,. Only when the two stage EO scale model was brought into operation was the more correct ratio of Watt-hours over treated volume of sludge adopted (Wh/L).

It is reported in literature that acceptable power consumption for electroosmotic dewatering is up to 140 kWh per cubic metre of volume feed sludge (<0.5 kJg^{-1}) (Van Diemen et al, 1989). Results which are shown in Table 8 compare very well with the quoted figure. The power consumption is found to be in a range between 20 and 100 kWh/m^3. Only in the case of anaerobically digested sludge from Mitchell's Plain and due to excessively high voltage used, the power consumption reached 230 kWh/m^3. It is, therefore necessary to optimise the operational conditions, such as voltage, belt speed, etc., in accordance with each type of sludge and its dewatering and electrical characteristics. This tailored operational criteria will facilitate the flexibility of the EO belt-press and its commercial value.

Attempts were made to measure the total power consumption. Three ammeters, one on each phase were installed. Unfortunately, very low observed current indication on two ammeters did not result in an accurate estimate of power consumption.

TABLE 8 : EXPERIMENTAL RESULTS FROM TWO STAGE DEWATERING SCALE MODEL

* Sludge type * No of sample	Feed (L)	Polyelectrolyte dosage (kg/Tds)	Solids concentration (%)			Voltage (V)	Electric power consumption (kWh/m³)
			Feed	Cake	Filtrate		
WAS - Borcherds Quarry No 5	45	1,5	1,7	10,7	0,26	8	100,5
AD - Mitchells Plain No 9	45	2,2	1,7	8,7	0,25	8	68,2
WAS - Atlantis No 3a	45	0,0	1,4	16,3	0,35	15	45,0
WAS Atlantis No 3b	33	2,3	1,6	16,2	0,58	10	24,4
WAS - Bellville No 4a	60	1,3	1,2	16,7	0,22	15	56,7
WAS - Mitchells Plain No 9	37	1,2	2,4	8,1	0,90	10	49,0
Centrifuged WAS No 20	105	0,0	9,4	12,3	0,90	8	20,8
AD - Mitchells Plain No 10	25	2,2	1,9	8,6	0,40	15	230,0
WAS - Stellenbosch No 12	50	1,3	0,9	14,2	0,28	15	63,8

* Table 1

TABLE 9 : CAKE SOLIDS CONCENTRATION AGAINST OPERATIONAL VARIABLES

* Sludge sample	Cake Solids Concentration (%)											
	Reduced Speed (25mm / min)						Increased Speed (100mm / min)					
	4mm gap			8mm gap			4mm gap			8mm gap		
	5V	10V	15V	5V	10V	15V	5V	10V	15V	5V	10V	15V
WAS - Borcherds Quarry No 5 ** c = 1,4 %	10,5	-	15,0	-	-	10,7	8,9	-	9,9	-	-	9,1
WAS - Scottsdene No 11 ** c = 0,7 %	13,2	-	14,9	-	-	-	10,0	-	12,7	-	-	-
AD - Mitchells Plain No 10 ** c = 1,7 %	6,7	8,7	-	4,7	5,8	-	4,8	6,1	-	4,4	5,4	-
WAS - Atlantis No 3a ** c = 0.8 %	-	16,2	20,1	-	-	-	-	-	-	-	-	-
Voëlvlei No 15 ** c = 2,6 %	-	-	13,9	-	-	-	-	-	12,4	-	-	-

* Table 1
* c = Initial solids concentration

6.3.6. *Cake solids concentration*

Results shown in Table 8 indicate that electroosmosis can be successfully applied to dewatering of activated sludges. Biological sludges contain highly compressible solids which give rise to gelatinous and thixotropic sludge cake generated by commercially available dewatering devices.

Final cake solids of the investigated No 4a (Table 1) WAS reached 16,7% (Table 8), with favourable cake consistency for beneficial re-use (composting) or safe and cost-effective final disposal.

Photographs shown in Figs 12, 13 and 14 illustrate the final sludge cake consistency generated by the electroosmotic process in combination with filter-belt pressing. In Fig 13 comparison of the waste activated sludge feed with final cake obtained from the experimental trial run is shown. As it can be seen from Fig 13 the pieces of sludge cake are well defined showing the crumbly sludge cake structure.

It is worth noting, as shown in Table 8, that anaerobically digested sludge (No 8 & 10, Table 1), in both runs, i.e. at 8 V and 15 V, achieved almost the same cake solids concentration of 8,7% and 8,6% respectively. It proves that a higher voltage is not necessarily effective for increase in dewatering rate. Besides, the anaerobically digested sludge from Mitchell's Plain, which is a mixture of activated and primary sludges, is known for it's difficult dewatering characteristic and when conventional laboratory dewatering tests were carried out, the highest sludge cake solids achieved were 5,5%. The electroosmotic runs produced 8,7%, and, what matters most, quite acceptable cake, capable of being safely utilised or disposed.

At the Mitchell's Plain Sewage Works, full-scale centrifugation trials were performed on activated sludges thickened by DAF unit. The centrifuged sludge cake sample of 105 litres was obtained for comparative experimental tests. The solids concentration of the centrifuged cake was found to be 9,4%. This cake was further subjected to the EO filter pressing, and due exclusively to electroosmotic action, the cake solids concentration was further increased to 12,3% consuming only 20,8 kWh/m^3 . However, the most beneficial outcome was that the cake produced by EO was crumbly and non-thixotropic.

The unique feature of anaerobically digested or activated sludge cake, generated by EO is it's superior handling properties, associated with significant improvement in cost-effectiveness of it's disposal or re-use.

6.3.7. *Sludge cake appearance*

The most significant feature of electroosmotically assisted sludge dewatering seems to be a crumbly appearance of a dewatered sludge cake. Drastic change of cake structure, due to a number of electrochemical processes takes place during electroosmotic dewatering (cake stratification, Chapter 5.3.1.). Significant cake volume reduction is attributed to the crumbly cake structure, which can not be achieved by any of the conventional dewatering methods.

This crumbly, hardened cake structure generated by electroosmotic dewatering makes transport and disposal not only much cheaper but also safer in respect to the sludge cake transport and final solids disposal (leachate reduction). Figs 12, 13 and 14 explicitely illustrate the significance of the EO process concerning final sludge cake appearance.

6.3.8. Solids content in filtrate

In order to calculate the mass balance, the solids content was determined separately on the three different filtrates obtained from gravity, mechanical and electroosmotic zone (Tables 10,11 and 12). In Table 8, the average of three filtrates solids content is given. Filtrate solids content from the EO section appears to be in the same region as from the remaining gravity and mechanical section of the filter-belt, i.e. between 0.2 and 0.9 %.

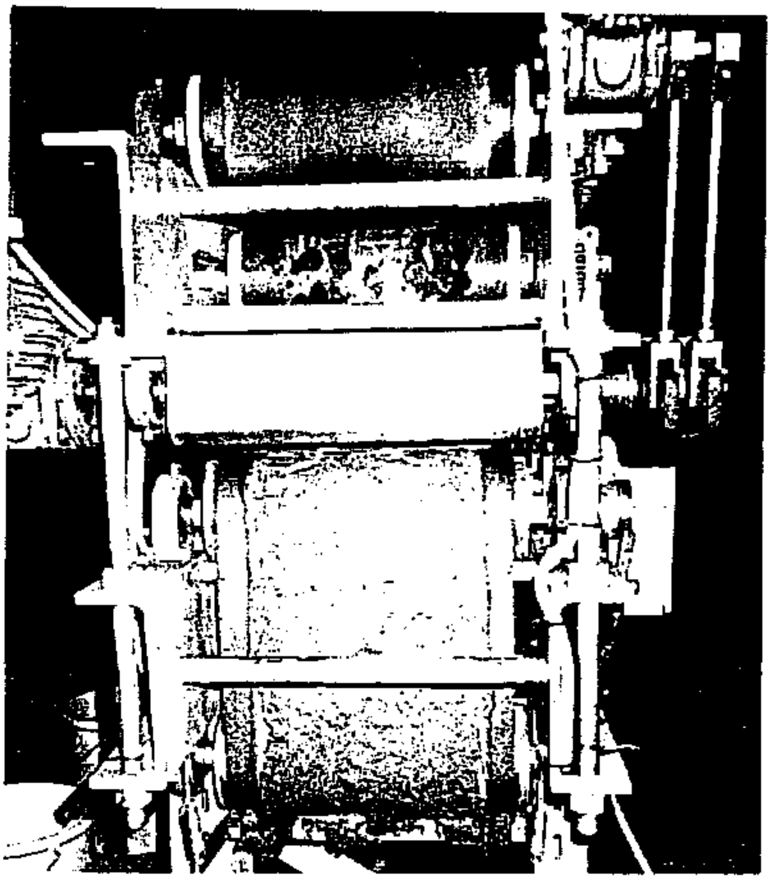


Figure 12 : Final sludge cake (WAS)

Figure 13 : Comparison between feed sludge and final sludge cake

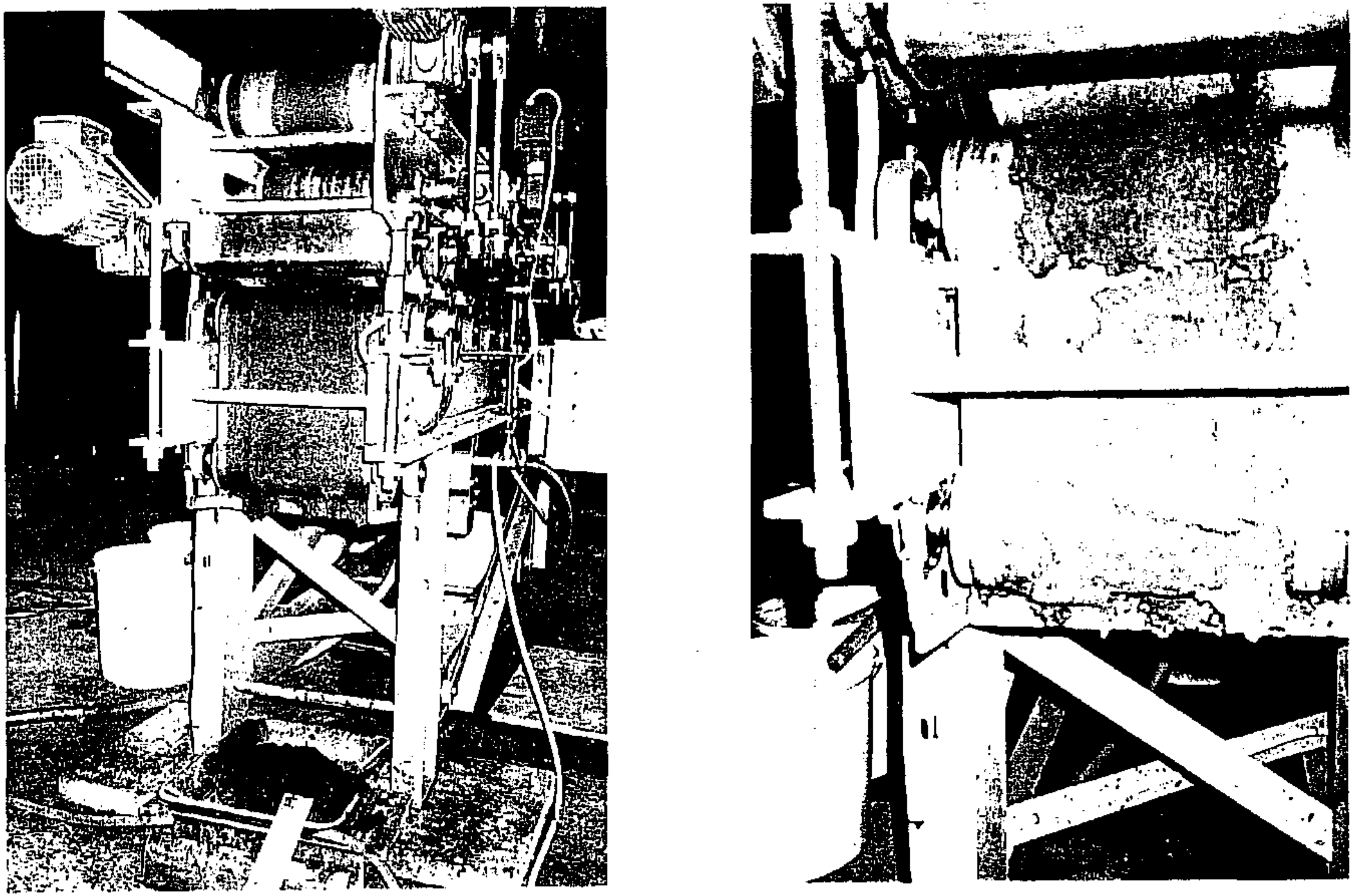


Figure 14 : Final sludge cake (DAF sludge)

6.3.9. *Mass and water balance*

The principle of mass balance concept is: inputs = outputs.

In Tables 10, 11 and 12 examples of water and mass balances are given. The water loss, possibly due to evaporation, Joule's heat effect and belts wetting was found to be in the range from 10 to 18 %.

Feed sludge total mass was found to be balanced by the sum of the sludge cake total mass plus the filtrate solids lost in the three separated sections of the plant, i.e., gravity, mechanical and electroosmotic. Solids in the belt washing water were also determined and added to the summary of the total mass of solids lost.

It appears that activated sludge solids can be balanced more easily than solids produced by anaerobic digestion (Tables 11 and 12 respectively), possibly due to more defined agglomerations of flocculated activated sludge particles.

6.3.10. *Throughput*

Throughput is an operational parameter which is determined by feed solids rate. Example of mass and water balance of an activated sludge in Table 10 shows that volume of 50 L and feed solids concentration of 9,1 g/L gives total mass input of 455 g during 2 hours of the experimental run. Because the plant was not run in a continuous, but in a batch mode of operation (for 2-3 hours), prediction of a full scale plant throughput cannot be based on the obtained results.

The most critical parameters affecting throughput is the speed and effective belt area. The experimental plant has limited belt speed, ranging only from 25 to 100 mm per minute. Furthermore, the mechanical and structural simplifications of the scale model did not provide for belt area to be effectively used. As a result, the belt, which width is only 300 mm, cannot be optimally loaded, for the sake of lateral sludge loss prevention. Because of these limitations, investigation of a throughput, to obtain information on full-scale performance, was not an issue.

TABLE 10 : MASS and WATER BALANCE - Waste Activated Sludge (Stellenbosch)

Sample		Volume (L)	Total solids (g/L)	Total mass (g)
Feed		50 (100%)	9,10	455,0 (100%)
Cake		2,8 kg* (5,6%)	141,7	396,8 (87,2%)
Filtrate	gravity section	36 (72,0%)	3,6	21,6 (4,7%)
	mechanical section	4,2 (8,4%)	1,9	8,0 (1,7%)
	electro-osmotic section	1,15 (2,3%)	3,1	3,5 (0,8%)
Water loss		5,85 (11,7%)	-	-
Belt washing		13,7	1,9	25,6 (5,6%)

* - *mass of sludge cake (assumed specific gravity of 1,0)*

TABLE 11 : MASS and WATER BALANCE - Waste Activated Sludge (Bellville)

Sample		Volume (L)	Total solids (g/L)	Total mass (g)
Feed		60 (100%)	12,2	732 (100%)
Cake		3,4 kg* (5,7%)	167,4	567,5 (77,5%)
Filtrate	gravity section	44 (73,3%)	3,3	145,2 (19,8%)
	mechanical section	2,9 (4,8%)	1,6	4,6 (0,6%)
	electro-osmotic section	1,9 (3,2%)	2,8	5,3 (0,8%)
Water loss		7,8 (13,0%)	-	-
Belt washing		11,2	1,8	9,4 (1,3%)

* - mass of sludge cake (assumed specific gravity 1,0)

TABLE 12 : MASS and WATER BALANCE - Anaerobically digested sludge (Mitchell's Plain)

Sample		Volume (L)	Total solids (g/L)	Total mass (g)
Feed		25,00 (100%)	18,64	466,00 (100%)
Cake		3,46* (13,8%)	86,14	298,04 (63,9%)
Filtrate	gravity section	10,45 (41,8%)	6,27	65,52 (14,0%)
	mechanical section	4,50 (18,0%)	3,17	14,26 (3,1%)
	electro-osmotic section	2,54 (10,2%)	3,03	7,70 (1,6%)
Water loss		4,05 (16,2%)	-	-
Belt washing		not determined	2,32	80,48 (17,3%)

* - mass of sludge cake (assumed specific gravity 1,0)

6.4. Recent experimental trials

Since this report was first written, some further tests were carried out. The results which are given in the previous chapters of this report are of a scientific nature, necessary for a refinement of the EO technology. Experimental trials with the purpose of providing commercial rather than scientific data were undertaken in order to identify a potential of the EO scale-model to produce the highest possible cake solids concentration with an acceptable magnitude of energy requirements.

6.4.1. Experimental procedure

Three different municipal sludges were subjected to the EO filter-press dewatering. In order to reach the highest possible cake solids concentration, the cake produced after first stage of electroosmosis was returned and put through EO section again and again, till filtrate separation became insignificant.

Retention time of sludge passing the gravity section was 9,2 minutes and 4,6 minutes, when subjected to the EO stage. Total retention time of sludge subjected to EO dewatering equals a number of repeated runs in EO section multiplied by 4,6 minutes.

Energy requirements were calculated from the ratio of Watt-hours over treated volume of sludge. This was than expressed in kWh per kg of dry solids.

Either no addition, or very low dosage of polyelectrolyte was maintained during the course of investigation.

6.4.2. Discussion of results

Summary of results is shown in Table 13. Three types of sludges which were investigated are characterised by different dewatering properties (Table 1). Good dewatering was obtained with No18 (Table 1) Zimpro sludge. Final cake solids of 44 percent was obtained, without addition of polyelectrolyte, at 23 minutes test duration. Anaerobically digested primary sludge, No 19 (Table 1), reached also high value of 45,0 percent solids concentration, but in the longer retention time of 46 minutes and with addition of 2,4 kg/tds. The most difficult WAS No 1 (Table 1), after 31,4 minutes, achieved 20,1 percent cake solids, with 2,0 kg/tds of the polyelectrolyte addition (Table 13).

Energy requirements

In Table 13 energy consumption is given in :

* kWh per cubic metre of sludge being dewatered
* kWh per kilogram of dry solids after dewatering

In order to compare the calculated values for energy consumption with those reported by other users of full-scale dewatering equipment (Pitman, 1994, STEINMÜLLER, 1994) the results are listed below:

	Energy consumption (kWh/kgds)
filter-belt press	0,11
filter press	0,16
decanter	0,09
EO filter-belt scale model	0,08-0,13

The comparison of energy consumption of the three commercially available dewatering machines with the EO scale model illustrates that the range of 0,08 to 0,13 kWh/kgds (Table 13), attributed to the EO dewatering does not exceed the values reported for the full-scale equipment.

It is anticipated that the power required for the operation of commercially available filter-belt presses will be higher than that used by the EO press. This is because the belt drive mechanism is simple, without mechanical pressure section, which features significantly in conventional belt pressing operation.

6.5 Industrial development

Upon completion of research and as a result of "in house" marketing, STEINMÜLLER (Africa) together with IDC became highly interested in joining CSIR in developing - in the first instance - of a demonstrator pilot-plant and eventually, of a full-scale EO filter-belt press, for local and European markets. An agreement with STEINMÜLLER has been signed at the end of 1994 and work on the pilot-plant design has started, with an intention of having it built by the middle of 1995.

TABLE 13 : Experimental results from EO scale-model (recent development)

* Sludge sample	Polyelectrolyte dosage (kg/Tds)	Initial concentration (%)	Retention time (EO section) (min)	Final cake solids (%)	Energy consumption ($kWhm^{-3}$)	(kWh/kgds)
Z - Milnerton No 18	0,0	7,8	13,8	44,4	33,8	0,08
AD (1) - Kraaifontein No 19	2,4	1,9	36,8	45,0	56,1	0,12
AS (1) - Athlone No 1	2,0	3,1	32,2	20,1	25,7	0,13

* Sludge sample

7. CONCLUSIONS AND RECOMMENDATIONS

There were four objectives of this investigation:

(1) The role of sludge liquid structure in sludge dewatering

(2) Laboratory investigation of electroosmotic dewatering

(3) Study of sludge dewatering using partly built (single stage) EO filter-belt scale model

(4) Investigation of sludge dewatering using the double stage EO filter-belt scale model

Investigation of the physical and chemical phenomena that occur in the interface of the electric double layer indicates the importance of individual liquids fixed in the sludge particle. Better understanding of the distribution of water and of the forces that bind water within the sludge may lead to better dewatering performance. Inefficiency of mechanical dewatering in removing liquids held within electric double layer (minute capillary structures), can be overcame by dewatering enhanced by electroosmosis.

From laboratory experimental results it was concluded that electroosmotic dewatering has the ability to remove the liquid which is hard to remove using conventional methods.

Scale model of a filter-belt device, in combination with electroosmotic dewatering was developed and partly build. It was found that the experimental results support the preceding laboratory results. It seems that EO can be particularly effective in dewatering of biological or chemical gelatinous and fine-particle sludges too difficult for mechanical dewatering.

Significant advantage of EO can be observed when applied in filtration processes. Blinding of the filter media, which is recognised as a major drawback of filtration, is markedly reduced by EO.

Upon completion of the EO two stage scale model and experimental trials the preceding findings were confirmed.

The uniqueness of the concept has been proven in the following respects:

The operational criteria can be tailored to each type of sludge which will provide greater flexibility in practical dewatering applications.

During electroosmotic dewatering major changes in cake structure take place which produce crumbly cake consistency, favourable for beneficial re-use or safe and cost-effective final disposal. This specific sludge cake consistency cannot apparently be achieved by the conventional dewatering methods.

Successful electroosmotic dewatering depends on electrical characteristics of the sludge. It is found that all investigated samples of waste activated sludges could be dewatered to an average solids concentration of 15% and consistency of a crumbly sludge cake, able to be stacked for further air drying or an easier and cheaper transport.

Efficiency of electroosmotic dewatering improves with the increase in initial sludge solids concentration. Therefore, sludge needs to be prethickened to a highest possible solids concentration, prior subjecting it to EO dewatering. Because there is a large installed capacity of centrifuges and vacuum filters, EO filter-belt press can be used to reduce moisture content of previously formed sludge cake.

A significant reduction in polyelectrolyte use is attributed to electroosmotic dewatering. Minimum dosage of 0,5 to 2,0 kg/Tds is recommended to be used for activated and anaerobically digested sludges respectively.

The reported high energy requirements (Chapter 4 and 5) are the result of calculations based on the ratio of Watt-hours over cumulative volume of filtrate recovered during the dewatering process. While this calculation do not detract from the scientific information given in these chapters, the basis for energy calculation in Chapter 6 is the ratio of Watt-hours over treated volume of sludge which gives more realistic prediction of the full-scale performance. According to this calculation the energy requirements for electroosmotic dewatering are found to be between 0,08 and 0,13 kWh/kgds, which does not exceed the values reported for the full-scale dewatering equipment such as centrifuges and belt and filter presses.

As a result of the recent experimental trials it was proved that the EO filter-belt press can dewater municipal sludge up to 45 percent solids concentration, which complies with world's most stringent sludge quality standards.

The EO experimental filter-press being a scale model of the full-scale plant can supply only general criteria to be used in the final design of a prototype pilot-plant due to it's practical limitation which preclude valid insight into variables such as throughput, belt speed, voltage, gap between belts, etc. The trials of the proposed technical scale pilot-plant will be the occasion when questions regarding operational variables can be investigated and answered.

The above findings are sufficient to justify the investment in a prototype pilot-plant which, upon incorporation of structural and mechanical improvements, can be optimised for factory production and sales as a proven unit.

Since this report was first written, further developments concerned with design and construction of the prototype pilot-plant have taken place.

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