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ELECTROOSMOTICALLY ENHANCED SLUDGE DEWATERING: PILOT-PLANT STUDY

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ABSTRACT

Owing to the inherent inefficiency of dewatering equipment widely used today, the search for improved dewatering techniques has been pursued by the investigation of new innovative ideas. The main thrust of these investigations has been in electroosmotic dewatering which presents a novel approach in South Africa.

The separation of the sludge liquid phase is governed by the intensity of binding forces. 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. It seems that the inefficiency of dewatering applied to gelatinous and fine-particle sludges can be overcome by mechanical dewatering enhanced by electroosmosis. A prototype pilot-plant embodying these principles has been developed for commercial application to dewatering of troublesome sewage sludges.

KEYWORDS

Sludge, electroosmotic dewatering, electric double layer, water distribution in sludges, pilot-plant dewatering.

INTRODUCTION

Optimisation of sludge treatment for achieving cost-effective dewatering is an important issue facing water authorities. Conventional treatment is no longer feasible. The separation of water from solids, or sludge dewatering, continues to be a major problem in waste water treatment. Unconventional approaches are being investigated with new equipment entering world markets. One of them is the use of electroosmosis for sludge dewatering. 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). There is, however, still lack of understanding of sludge particle surface properties which is essential for the optimisation of dewatering technologies. Different physical states of water and their distribution play a significant role in the dewatering behaviour of sludges.

The response of different sludges to electroosmotic dewatering was investigated using bench-scale and prototype pilot-plant equipment. Encouraging results from both studies warrant development of the prototype electroosmotic pilot-plant for future commercial application.

This paper deals with the electroosmotic pilot-plant investigation.

BACKGROUND INFORMATION

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-floc cannot be classified merely as "free" and "bound".The assumption that water within a sludge-floc 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;

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).

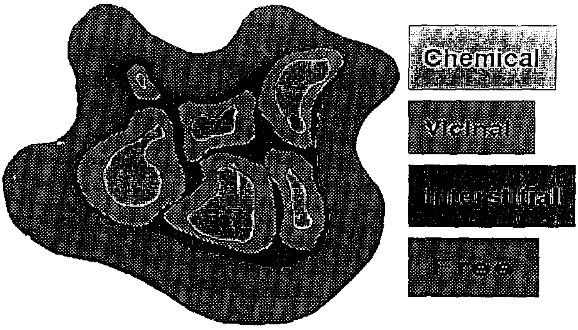

Fig. 1. Water distribution in sludge-floc

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-floc. The prime characteristic of sludge particles is their large surface area. This provides not only a highly chemically active surface area but also allows for 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: (i) Newtonian fluids, (ii) Smoluchowski liquids, and (iii) 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.

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 thicknesses. 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 potential and represents the repelling force of the particle, opposite to attractive van der Waals forces. Zeta potential is interpreted in terms of the potential at the boundary between the fixed and the mobile parts of the double layer.

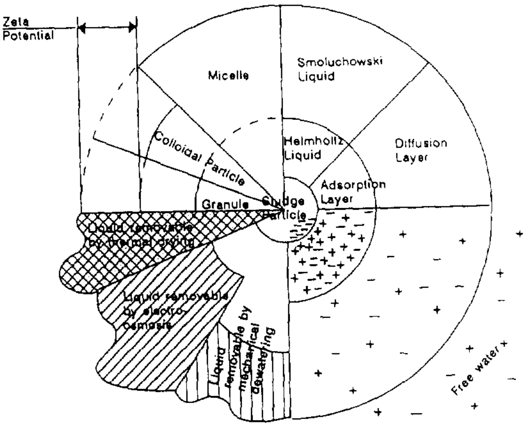

Fig. 2. Sludge-particle liquid in an electric double layer in relation to the moisture removal method

Electroosmosis

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, 1965).

An electrokinetic phenomenon such as electroosmosis arises when an 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 sign of the charge it carries. In the classical studies of early research (about 1850) mass flow rate during electroosmosis was found to be independent of a porous diaphragm immersed in water or other liquid. A 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.

Liquid fractions in relation to methods of sludge dewatering

Sludge dewatering enhanced by electroosmosis 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).

Studies 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 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 made to illustrate graphically (Fig.2) 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 the 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 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.

STUDY OF SLUDGE DEWATERING BY PILOT FILTER-BELT IN COMBINATION WITH ELECTROOSMOSIS

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

The EO filter-belt scale model

In Fig. 3 the double stage scale model of the EO filter-belt press is illustrated. Due to financial constrains this arrangement was simplified. A schematic diagram of the simplified one stage model (as it has been build) is shown in Fig.4. The plant consists of a feed box, horizontal belt gravity dewatering section and an electroosmotic section, where sludge is squeezed between two belts. Belts are made of an 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 moves to the cathode, and the negatively charged sludge particles to the anode electrode.

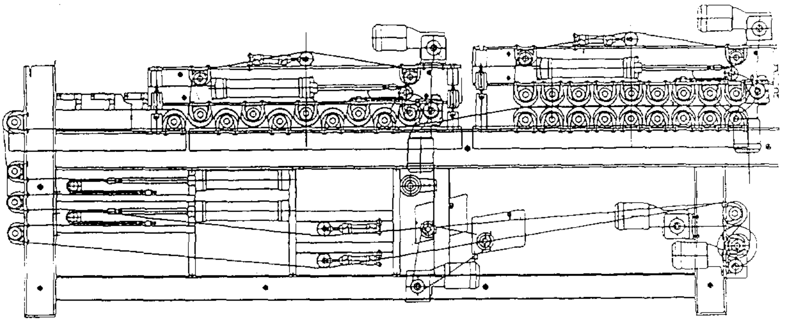

Fig. 3. EO double stage filter-belt press

Experimental

EO filter-belt experimental runs were performed on activated and anaerobically digested sludges collected from seven different waste water treatment works in the Wastern Cape area.

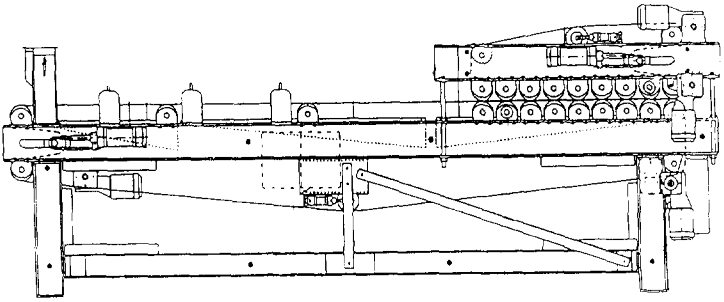

Fig. 4. EO single stage filter-belt press

The experiments were performed on sludges with and without addition of polyelectrolyte. Minimal dosage of a polyelectrolyte (up to 2 kg/t.d.s) was maintained by visual assessment of the first signs of sludge flocculation, which indicated the minimal amount of polymer required. For comparison purposes relatively high dosages of polyelectrolyte (3 to 6,5 kg/t.d.s) 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 pilot-plant 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 electroosmosis 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 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:

* solids concentration prior to pilot-plant dewatering;
* 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 second 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.

Results and discussion

The pilot-plant experimental results are illustrated in Tables 1, 2, and 3. In order to obtain as much information as possible on the response of different type of sludges to pilot-plant 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.

Batch dewatering at constant voltage

The pilot-plant experimental runs were carried out at constant voltage and the following observations were made.

The amperage values increase when wet sludge enters the electroosmotic section, and decrease as dewatering progresses. The electric current decreases with time because of the increase in electric resistance caused by the decrease in water content. At the end of batch dewatering, the sludge layer, near the upper electrode, appears to be completely dewatered. The sludge cake separates into two layers:

- the dewatered upper layer of different, much lighter colour;
- the darker in colour, underdewatered lower layer.

No significant blinding of the filter-belt material was observed. As sludges generally 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.

There is an optimum operating condition with regard to dewatering rate and electrical power consumption, also predicted by previous laboratory investigation. A higher voltage is not necessarily effective for increasing the dewatering rate. It is shown in Table 2 that activated sludge from Borcherd's Quarry reached cake solids concentration of 12,7% at 10V, after the 1st stage of dewatering, using only 193 Wh/L. When it was subjected to the 2nd stage of dewatering at 20V, the energy requirement was almost six times higher than in the 1st stage and only slight cake solids increase, to 14,7%, was achieved.

The energy requirements increase with increase in voltage, in some cases reaching very high values. It appears that dewatering of anaerobically digested sludges requires 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 electrical double layer on anaerobically digested than on activated sludge particles. This results in a higher energy requirements for removal of 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 electric resistance. Current intensity is dictated by voltage and electrical conductivity of the liquid phase. When electrical conductivity is very high, high electric power is required. 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.

Effect of addition of polyelectrolyte

Addition of polyelectrolyte was necessary in order to improve solids-liquid separation in the gravity section of the pilot-plant. No improvement in cake solids concentration due to polymer addition was obtained after electro-osmotic dewatering of activated sludges. Activated sludge from Scottsdene at 15V reached 10,3% without polymer (Table 1), 9,2% with low polymer dosage (Table 2), and 9,2% with high dosage (Table 3). It appears that the very difficult to dewater anaerobically digested sludges

TABLE 1 : EXPERIMENTAL RESULTS FROM ELECTROOSMOTIC PILOT PLANT (NO POLYELECTROLYTE)

		1st stage of dewatering					2nd stage of dewatering				
		0V	5V	10V	15V	20V	0V	5V	10V	15V	20V
Activated - Scottsdene	%	4,4	6,3	7,1	10,3	9,4	5,3	9,4	10,6	13,2	15,0
c = 1,8 %	L/Ah	-	0,11	0,03	0,03	0,07	-	0,08	0,03	0,04	0,04
(after gravity settling)	Wh/L	-	44	354	458	664	-	59	368	413	522
Activated - Mitchell's Plain	%	5,7	-	6,3	-	8,1	7,0	-	8,7	-	9,1
c = 4,3 %	L/Ah	-	-	0,04	-	0,06	-	-	0,21	-	0,01
(after gravity settling)	Wh/L	-	-	250	-	356	-	-	459	-	1603
Anaerobically digested	%	-	-	-	6,1	-	6,1	-	-	-	10,0
Cape Flats	L/Ah	-	-	-	0,02	-	-	-	-	-	0,015
c = 1,7 %	Wh/L	-	-	-	1000	-	-	-	-	-	1326

c - initial solids concentration

from Cape Flats and Mitchell's Plain are positively affected by the polyelectrolyte addition, reaching 16,3% and 22,6% cake solids respectively.

Effect of addition of polyelectrolyte appears to depend on the type of sludge and it's 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 polyelectrolyte, the amount of electrical current is proportional to the remaining charge. In the electrical double layer the counterion layer becomes a net residual ionic charge of the particle. Addition of polymer 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 polymer (Table 1) and decreases with increased polymer dosage (Tables 2 and 3) i.e. activated sludge from Scottsdene at 15V showed 458 Wh/L (no poly), 358 Wh/L (low dosage) and 103 Wh/L (high dosage).

TABLE 2 : EXPERIMENTAL RESULTS FROM EO FILTER-BELT PRESS (WITH LOW POLYELECTROLYTE DOSAGES: 0,5 to 2,0 kg/t.d.s)

		1st stage of dewatering					2nd stage of dewatering				
		0V	5V	10V	15V	20V	0V	5V	10V	15V	20V
Activated - Borcherd's Quarry	%	7,8	-	-	12,7	-	9,8	-	-	14,7	-
c = 1,8 %	L/Ah	-	-	-	0,08	-	-	-	-	0,01	-
(DAF)	Wh/L	-	-	-	193	-	-	-	-	1130	-
Activated - Borcherd's Quarry	%	7,3	-	-	8,1	-	9,7	-	-	13,6	-
c = 2,3 %	L/Ah	-	-	-	0,06	-	-	-	-	0,02	-
(after gravity settling)	Wh/L	-	-	-	258	-	-	-	-	708	-
Activated - Scottsdene	%	5,4	7,2	8,6	9,2	10,0	6,3	9,1	12,1	12,2	12,2
c = 1,3 %	L/Ah	-	0,08	0,04	0,04	0,06	-	0,08	0,04	0,03	0,05
(after gravity settling)	Wh/L	-	60	249	389	311	-	60	226	480	394
Activated - Mitchell's Plain	%	5,6	-	6,0	-	6,8	7,9	-	8,3	-	10,0
c = 3,6 %	L/Ah	-	-	0,07	-	0,03	-	-	0,02	-	0,03
(after gravity settling)	Wh/L	-	-	145	-	597	-	-	413	-	565
Anaerobically digested	%	15,8	-	16,0	16,3	19,4	20,0	-	21,8	24,5	28,1
Cape Flats	L/Ah	-	-	0,05	0,06	0,04	-	-	0,04	0,09	0,02
c = 4 %	Wh/L	-	-	223	259	577	-	-	272	170	1215

c - initial solids concentration

Since this paper was first written it was found that the calculation of the energy requirements had to be changed when proceeding with the two stage scale model investigation. The energy calculation in this paper is based on the cumulative volume of filtrate recovered during the dewatering process, ignoring such factors as water lost due to evaporation, water adhering to the apparatus (belt wetting) etc,. As a result, very high energy requirements are reported (Tabs 1,2 and 3). While this high energy calculation does not detract from the scientific information given in this paper, more realistic approach has to be adopted in the further studies. This will involve ratio of Watt-hours over treated volume of sludge, instead of Watt-hours over cumulated volume of water removed.

TABLE 3 : EXPERIMENTAL RESULTS FROM EO FILTER-BELT PRESS (WITH HIGH POLYELECTROLYTE DOSAGES: 3,0 to 6,5 kg/t.d.s)

		1st stage of dewatering					2nd stage of dewatering				
		0V	**5V**	**10V**	**15V**	**20V**	**0V**	**5V**	**10V**	**15V**	**20V**
Activated - Package Plant	%	-	-	-	9,6	-	-	-	-	17,2	-
c = 1,3 %	L/Ah	-	-	-	0,08	-	-	-	-	0,13	-
(after gravity settling)	Wh/L	-	-	-	194	-	-	-	-	116	-
Activated - Stellenbosch	%	7,9	8,2	8,9	9,8	10,0	9,6	11,0	11,9	13,5	13,8
c = 1,3 %	L/Ah	-	0,10	0,08	0,06	0,04	-	0,10	0,06	0,06	0,03
(after gravity settling)	Wh/L	-	47	117	267	500	-	50	161	276	599
Activated - Scottsdene	%	6,8	7,6	-	9,2	-	9,5	10,6	-	14,9	-
c = 1,1 %	L/Ah	-	0,15	-	0,15	-	-	0,09	-	0,07	-
(after gravity settling)	Wh/L	-	33	-	103	-	-	54	-	202	-
Activated - Cape Flats	%	8,6	-	-	9,0	-	10,4	-	-	14,6	-
c = 2,3 %	L/Ah	-	-	-	0,06	-	-	-	-	0,06	-
(DAF)	Wh/L	-	-	-	268	-	-	-	-	294	-
Anaerobically digested	%	7,3	-	8,5	7,1	8,2	8,1	-	11,6	12,8	16,3
Cape Flats	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
Anaerobically digested	%	6,0	10,0	12,5	11,7	13,6	11,3	13,2	16,8	19,0	22,6
Mitchell's Plain	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

c - initial solids concentrate

CONCLUSIONS

The objectives of this investigation were twofold:

1. The role of sludge liquid structure in sludge dewatering;
2. Initial study of sludge dewatering using EO filter-belt scale model in combination with electroosmosis;

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. A 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 overcome by dewatering enhanced by electroosmosis.

Scale model filter-belt device, in combination with electroosmotic dewatering was developed and partly built. It was found that the initial experimental results support the preceding laboratory results. It seems that electro-osmosis can be particularly effective in dewatering of gelatinous and fine-particle sludges which are difficult for mechanical dewatering. Significant advantage of electroosmosis can be observed when applied in filtration processes. Blinding of the filter media, which is recognised as a major drawback of filtration processes, is markedly reduced by electroosmosis. A significant reduction in polyelectrolyte use is also attributed to electroosmotic dewatering.

The reported excessively high energy requirements are the result of calculations based on the ratio of Watt-hours over cumulative volume of filtrate recovered during the dewatering process. While this high energy calculation do not detract from the scientific information given in this paper, the basis of future calculations will be the ratio of Watt-hours over treated volume of sludge.

The experimental results warrant the development of the two stage EO filter-belt press for further investigation of electroosmotically assisted sludge dewatering technology.

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