Fundamentele aspekten van slibontwatering ; Deel 8 : Congresbijdragen

8

i g e

r i o o l w a t e r -

z u i v e r i n g s i n r i c h t i n g e n

rwzi
2000

FUNDAMENTELE ASPEKTEN VAN SLIBONTWATERING

Deel 8: Congresbijdragen

Rijkswaterstaat
Rijksinstituut voor Integraal Zoetwaterbeheer
en Afvalwaterbehandeling

Postbus 17, 8200 AA Lelystad

Stichting Toegepast Onderzoek
Waterbeheer

Postbus 8090, 3503 RB Utrecht

generatie rioolwaterzuiveringsinrichtingen RWZI 2000

projectleiding en secretariaat: postbus 17, 8200 AA Lelystad 03200 - 70411

rwzi 2000

FUNDAMENTELE ASPEKTEN VAN SLIBONTWATERING

Deel 8: Congresbijdragen

auteur(s):

TU-Eindhoven, Laboratorium voor Scheidingstechnologie:

ir. A.J.M. Herwijn
drs. E.J. La Heij
ing. P.M.H. Janssen
dr.ir. W.J. Coumans
prof.dr.ir. P.J.A.M. Kerkhof

RWZI 2000 94-02

Het onderzoek "Toekomstige generatie rioolwaterzuiveringsinrichtingen RWZI 2000" is een samenwerkingsverband van de STOWA en Rijkswaterstaat (RIZA).

VOORWOORD

*De problematiek rond de nuttige afzet van zuiveringsslib heeft binnen het RWZI 2000 onderzoek-*programma ruim aandacht gekregen. Naast kwaliteitsverbetering van zuiveringsslib kan de omvang van het probleem worden verkleind door het volume van de hoeveelheid slib, dat vrij komt te beperken. Enerzijds door een verminderde produktie van slib bij het zuiveren van rioolwater, anderzijds door het drogestofgehalte van het gevormde zuiveringsslib te verhogen o.a door een verbeterde ontwatering. Aangezien destijds met de toenmalige, veelal op empirisch onderzoek gebaseerde inzichten en kennis geen substantiële verhoging van het drogestofgehalte was te verwachten, is in 1990 een fundamenteel onderzoek gestart naar slib/waterscheiding.

Het onderzoek is uitgevoerd in het Laboratorium voor Scheidingstechnologie van de TU-Eindhoven door een projektgroep, bestaande uit ir. A.J.M. Herwijn, drs. E.J. La Heij en ing. P.M.H. Janssen onder begeleiding van dr.ir. W.J. Coumans en prof.dr.ir. P.J.A.M. Kerkhof. Een belangrijke bijdrage aan het onderzoek is geleverd door tien afstudeerders van de faculteit Scheikundige Technologie.
Bij de uitvoering van het onderzoek werd het projectteam begeleid door een commissie bestaande uit ir. H.A. Meijer (Zuiveringsschap Hollandse Eilanden en Waarden), prof.ir. J.H.J.M. van der Graaf (TU-Delft/Witteveen & Bos), ing. R. Kampf (Hoogheemraadschap Uitwaterende Sluizen), ir. R.E.M. van Oers (Hoogheemraadschap West-Brabant), prof.dr.ir. W.H. Rulkens (LU-Wageningen), ing. G.B.J. Rijs (RIZA) en ir. P.C. Stamperius (STOWA).

Het voorliggende rapport geeft een overzicht van de verkregen onderzoeksresultaten en vormt een onderdeel van het uit acht deelrapportages bestaande eindrapport, t.w.:

- deel 1: Samenvattend verslag
- deel 2: Flocculatiemechanismen
- deel 3: Filtratie-expressie modellering
- deel 4: Filtratie-expressie experimenten
- deel 5: Slib-water binding
- deel 6: Karakterisering van slibben
- deel 7: Ontwikkeling nieuw CST-apparaat
- deel 8: Congresbijdragen

Lelystad, juli 1994

Voor de Stuurgroep RWZI 2000

prof. dr. J. de Jong
(voorzitter)

DANKWOORD

Onze dank gaat uit naar de studenten die in de projectgroep hun afstudeerwerk hebben verricht en een grote bijdrage hebben geleverd aan het onderzoek: Albert van Veldhuizen, Lotte Boon, Paul Dohmen, Frank Pijpers, Juul IJzermans, Diederic van Dijke, Oscar Meijer, Marga Verduin, Annemiek van der Zande en Moshe van Berlo.

Gerben Mooiweer wordt bedankt voor zijn bijdrage aan het ontwikkelen van rekenprogramma's.

Leo Pel van de faculteit Bouwkunde en Klaas Kopinga van de faculteit Technische Natuurkunde bedanken wij voor het deskundige advies en het beschikbaar stellen van de NMR-apparatuur.

Paul Buijs, Wies van Diemen en Prof. Stein van de vakgroep Thermodynamica en Colloïdchemie worden bedankt voor het beschikbaar stellen van de het ESA-meetinstrument.

Jan Denissen van TNO-keramiek wordt bedankt voor het fabriceren van keramiek voor het gemodificeerde CST-apparaat.

De technici, bedankt voor jullie ondersteuning bij het ontwerpen en bouwen van meetopstellingen.

Anniek van Bemmelen en May Rijvers bedanken wij voor het verzorgen van het eindrapport.

Namens de projectgroep.

Prof.dr.ir. P.J.A.M. Kerkhof

INHOUDSOPGAVE

SOME FUNDAMENTAL ASPECTS OF SLUDGE DEWATERING

Ir. A.J.M. Herwijn, Dr.Ir. W.J. Coumans and Prof.dr.ir. P.J.A.M. Kerkhof

1 Introduction

Because of the more severe legislation there is a need to find other solutions than disposal of dewatered sewage sludge on dumping sites and in agriculture. Smaller sludge volumes and smaller dewatering systems are needed. Other disposal options that are of interest now, are combustion and drying of dewatered sludges. Increasing the dry solids content of the dewatered sludge reduces the energy needed for combustion and drying. Volume reduction of the dewatered sludge can be reached in two ways:

1. Reduction of the production of sewage sludge by optimizing the existing waste water treatment plants.
2. Improving existing techniques or developing new techniques for dewatering sewage sludges. The basic aim is to achieve higher dry solids content of the sludge cake.

By getting more insight into the physical and physico-chemical processes involved in the sludge dewatering process can help us to improve the dewatering characteristics (high dry solids content and/or more rapid dewatering) of existing techniques.

In the beginning of 1990 we started a study of some fundamental aspects of sludge dewatering in our laboratory, within the larger Dutch research program entitled "Future treatment technique for municipal waste water (shortly RWZI 2000)". Participants in the study are Ir. A.J.M. Herwijn, Drs. E.J. La Heij and Ing. P.M.H. Janssen. The end responsibility is accepted by Dr.Ir. W.J. Coumans and Prof.Dr.Ir. P.J.A.M. Kerkhof. The study is financially supported by the "Institute of Inland Water Management and Waste Water Treatment (RIZA)" and the "Foundation for Applied Waste Water Research (STORA)".

One part of the study is aiming for the understanding of physical and physico-chemical phenomena occurring on microscale, and how these phenomena manifest themselves on the macroscopic scale. Important are the crosslinks between physical parameters, determined with various characterization methods. Another part of the study is the development of theoretical and simulation models predicting filtration and expression behaviour. These type of models could then be used in the optimization of dewatering processes and equipment parameters.

2 The presence of water.

In figure 1 we present schematically the way that water may be present in sludge and sludge cakes. In a suspension or in a filter cake we may distinguish a water phase and a floc phase. The flocs are formed from the basic sludge particles, in many cases with the addition of flocculants. Flocculants are used to promote the aggregation of basic particles and in this way improve the release of water of sludges. Flocculants that are usually applied in waste water treatment plants are $FeCl_3/Ca(OH)_2$ and polyelektrolytes.
The mechanical behaviour of flocs in a dewatering process depends on floc properties and conditions of dewatering as well. Floc properties of a given sludge depend on amount and nature of the flocculants. The flocs consist of a skeleton, in which interstitial liquid is present.
The properties of the basic sludge particles vary with place, season and conditions in the waste water treatment plant. Basic particles, like microbial cells, or pieces of wood, etc. contain water inside. Further we will have hydration layers at the particle surfaces.

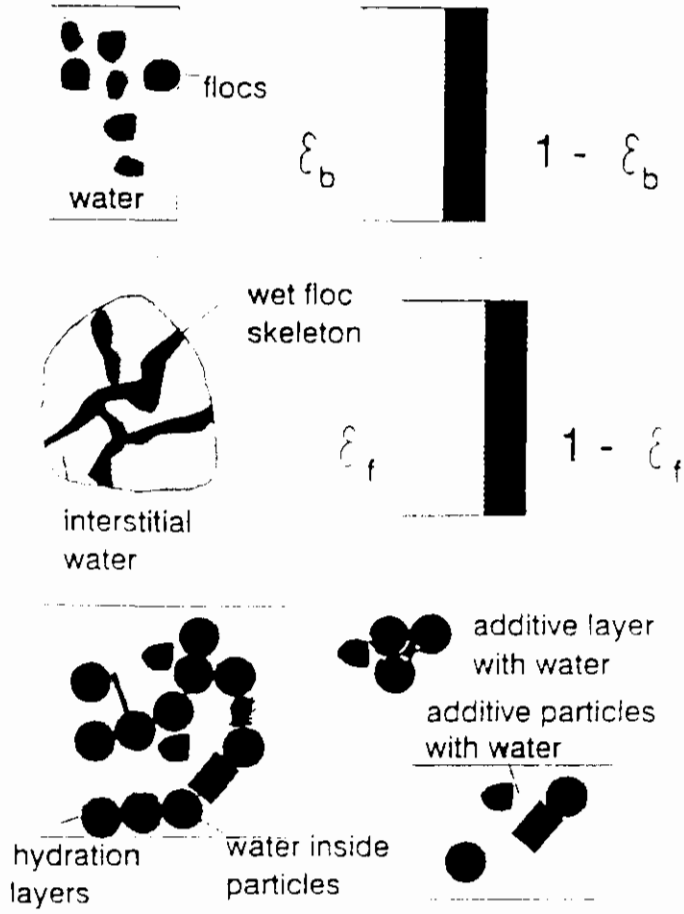


Fig. 1 Schematic representation of water in sludge

3 Mechanical dewatering.

After a sedimentation step further sludge dewatering is performed by means of filtration and expression. In filtration and expression the water phase moves relative to the solids and/or flocs under the influence of a gradient in liquid pressure. Dewatering techniques used in practice are the chamber filter press and the belt press and to a certain amount also the centrifuge.

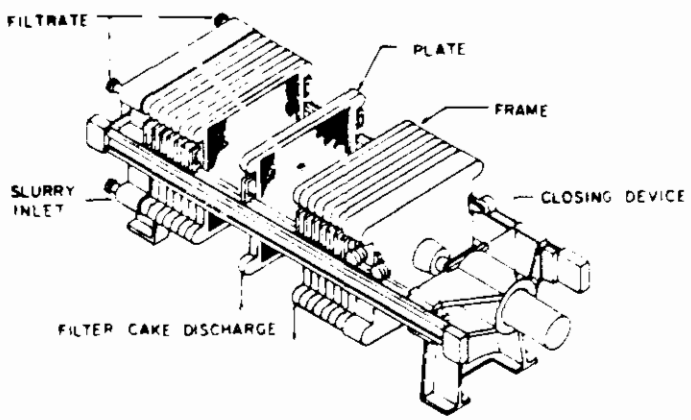


Fig. 2 The chamber filter press.

The conventional chamber filter press is a batch-operating pressure filter (fig. 2). Frames and corrugated plates are arranged alternately and supported on a pair of rails. The sludge is introduced through a port in each frame and the filtrate passes through the cloth on both sides of the frame. The liquid runs down the corrugated surface of the plates. Two cakes are formed simultaneously in each chamber. The process is stopped if the two cakes join, the chambers are opened and the cake is discharged. The types of flocculants that are used in this dewatering technique are $FeCl_3/Ca(OH)_2$

The belt filter press is a continuous pressure filter (fig. 3) which usually combines gravity drainage with mechanical squeezing of the cake between two running belts. Liberated water passes through the belts. Polyelektrolytes are the type of flocculants used in this technique.

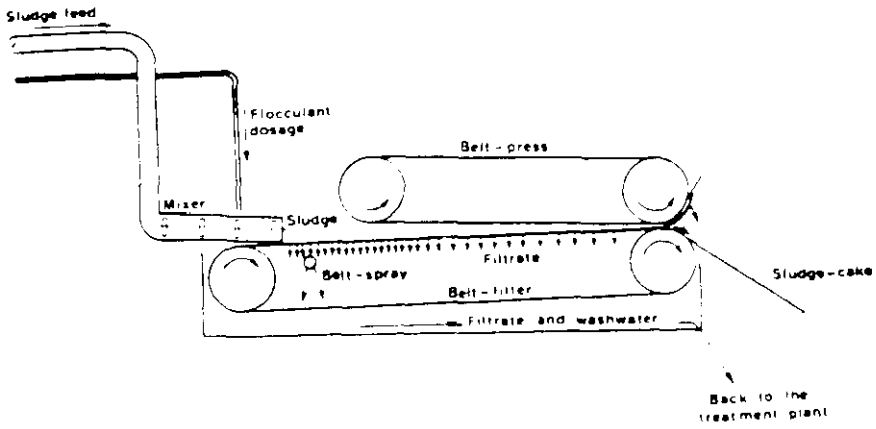


Fig. 3 Flow scheme of the belt filter press.

4 Characterization of sewage sludge.

Characterization of sewage sludge means determining chemical and physical properties, which are of importance in the dewatering process. I will give some results concerning a few characterization methods available in our laboratory.

a. Particle size distribution and particle morphology.
These two characteristics represent the initial conditions of the flocs as they enter the dewatering process. Besides laser-diffraction equipment also the optical image technique and electron microscopy are important to get impressions of irregularities in shape, and of structure.

b. Water binding and transport.
Since water may be present in various ways, it is of interest to quantify the several types of water.
Drying experiments on filter cakes may be analysed in terms of an effective water diffusion coefficient and its concentration dependence. The value of the effective diffusion coefficient is a measure for the bond strength between solids and water. From a drying experiment also information about the amount of free and bound water can be obtained. If in a drying experiment the rate of evaporation remains constant, free water is transported and mass transfer is limited by external drying conditions. A decreasing rate of evaporation indicates that mass transfer is limited by diffusion in the sludge cake.
In a drying experiment, which is carried out in thermal analysis equipment, weight loss and the energy required for evaporation are measured simultaneously. With these data the bond energy between sludge particle and water can be calculated as a function of the water content of a sludge cake sample. In figure 4 a result is given. Lowering the water content of a sludge cake sample from 5% increases

the bond energy enormously. So it is very difficult to release the last remainders of water in a sludge sample by mechanical means. This information is of importance for a better understanding of the drying process of sewage sludges.

Freezing curves of sludge cakes may also provide information on the amounts of free and bound water. Bound water is by definition not available for crystallization. The bond energy of the bound water is larger than 330 kJ/kg, being the crystallization energy of free water. From these experiments it can be concluded that the bound water content of a sludge cake is about 0.4 kg water/kg dry solids.

The water vapour isotherm, which is the equilibrium relation between the water content of a sludge cake sample and the relative humidity of the surrounding atmosphere, provides additional information on the bound water. This information can be obtained in two ways:

a. A decreasing relative humidity with decreasing water content of the sample indicates the presence of bound water in the sample.
b. By measuring sorption-isotherms at different temperatures the bond energy can be quantified as function of moisture content using the Clausius-Clapeyron equation.

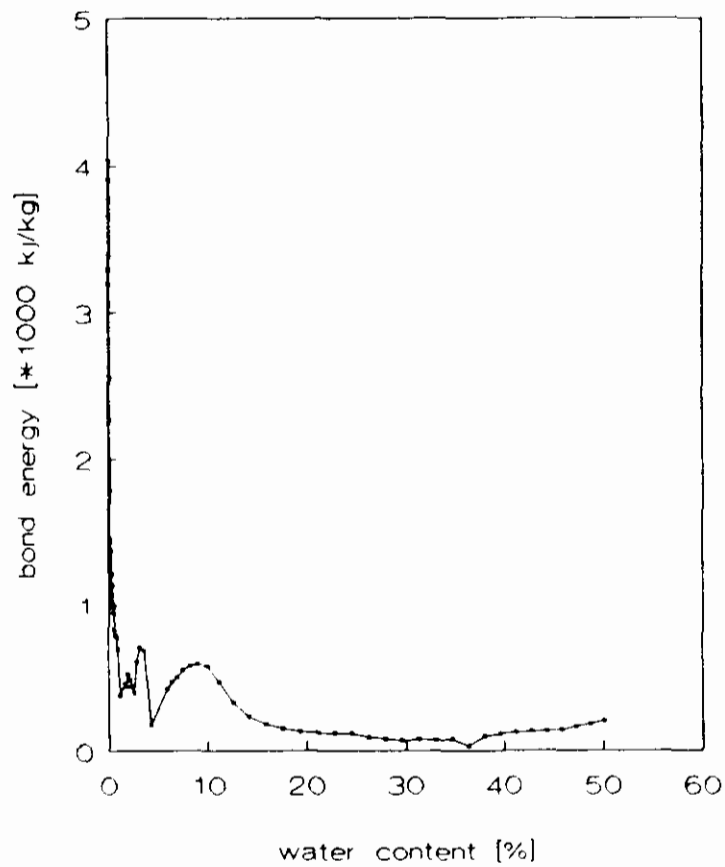


Fig. 4 Bond energy as a function of water content of a sludge sample.

c. Physico-chemical aspects.

For a better understanding of the dewatering process we study the colloid-chemical aspects. Interesting elements of study are floc formation, strength and structure and the consequences for the engineering aspects. Measurements of zeta-potentials for various additives are carried out to study floc formation processes. The zeta-potential of a sludge sample is determined with the Electrokinetic Sonic Analysis System. The floc formation process, which occurs when a certain amount of $FeCl_3$ is introduced in a sludge sample, is known as sweep flocculation. The metal ions form metal hydroxide complexes in the aqueous solution, which adsorb at the sludge particle surface. Sludge particles surrounded by layers of metal hydroxide complexes stick to each other and so flocs are formed.
By measuring the reological properties of a sludge sample with a Couette-rheometer, the strength of flocs can be determined.

5 Theoretical and experimental investigation into the solid-liquid separation process.

The conventional filtration theory has been derived for particles with a closed surface. It is known that flocs may have an open structure (see fig. 1). Therefore Kerkhof [1] developed the "DUAL FLOW MODEL", which takes into account that water flows both through the pores between the flocs and through the flocs themselves. Thus, compared with the conventional approach, now the liquid between the flocs is less decelerated at the floc surface for a given pressure gradient.
Further, the model allows the estimation of the effective permeability of a bed with permeable particles. The effective permeability of a bed depends on the porosity of the filter cake ϵ_b and the internal floc porosity ϵ_f (see fig. 1).
From simulations we may conclude that the flow through the flocs causes a large increase of the bed permeability especially for lower sludge cake porosities ($\epsilon_b < 0.1$). See fig. 5.
The "DUAL FLOW MODEL" is a good base for further refinement and experimental study. It will be especially of interest to investigate the separate deformations of flocs and filter beds in a filtration or expression process. Now deformation means that the porosities of both the floc and the filter bed change and so the effective permeability of the filter bed will be influenced.

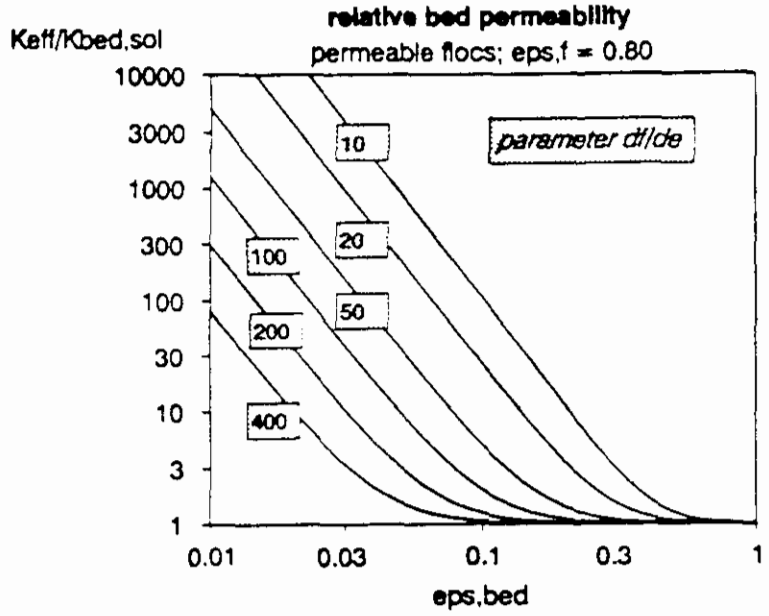


Fig. 5 Relative permeability of porous floc bed K_{df} compared to closed particles K_{bsol}, as a function of bed porosity eps,bed with relative floc size df/de as parameter; df = floc diameter, de = diameter of elementary floc particles. Floc porosity eps,floc = 0.80.

The model description of filtration and expression requires a more detailed analysis. However, interesting observations for practice can be obtained from laboratory tests, such as filtration of a sludge sample under constant gas pressure. By fitting the experimental relation of filtrate volume over time, we find an average value of the specific cake resistance. In fig. 6 we see the influence of the addition of $FeCl_3$ on the specific cake resistance. It is clear that the resistance decreases upon addition to a limiting value. The decrease is quite strong.

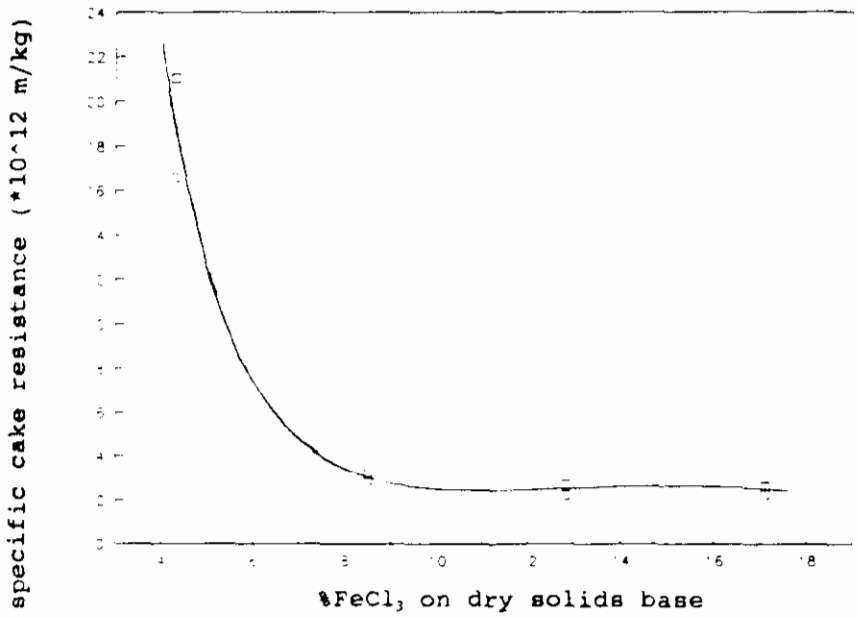


Fig. 6 Specific cake resistance as a function of the amount of added FeCl3.

Another laboratory test is the compression-permeability cell. In this cell the compression behaviour of a sludge cake can be studied. With this device the empirical relationship between cake porosity and cake permeability can be determined. Also the relation between cake porosity and compression pressure can be measured. These empirical relations provide basic data for the "DUAL FLOW MODEL".
Increasing pressure during a filtration cycle usually decreases the liquid content of filter cakes. However, highly compressible cakes, like sewage sludges, do not respond directly to an increase of filtration pressure. During filtration of sewage sludge a skin with a low porosity and a high flow resistance is developed next to the filter medium (porous sheet or cloth). To improve deliquoring of such cakes, the direction of the liquid flow can be reversed at the end of the filtration process. When reverse flow takes place, the skin serves as a piston which compresses the unconsolidated portion of the cake. In this way lower final moisture contents in filter cakes can be achieved. An experimental device will be developed to study this phenomenon.

6 Final remarks.

In the study of some fundamental aspects of sludge dewatering we try to get a better understanding of the sludge dewatering process. Therefore, sludge is characterized in several ways. It is important to find crosslinks between physical parameters determined with the characterization tests. Another important element of study is the theoretical description of the dewatering process. Hopefully, new insights can be used for optimization of process conditions and design of new dewatering equipment in the future.

References.

1. Kerkhof, P.J.A.M.
Some fundamental aspects of sludge dewatering.
Netherlands-Japan workshop "municipal waste treatment", Lelystad, april 1991.

2. Coumans, W.J., Kerkhof, P.J.A.M.
Karakterisering en ontwatering van zuiveringsslibben.
Symposium 'RWZI 2000', Ede, oktober 1989.

SOME FUNDAMENTAL ASPECTS OF SLUDGE DEWATERING

Piet J.A.M. Kerkhof

(Laboratory for Chemical Process Engineering, Dept. of Chemical Engineering, Eindhoven University of Technology, P.O.Box 513, 5600 MB Eindhoven, the Netherlands)

SUMMARY

An overview is given of major fundamental aspects of sludge dewatering. First the presence of water in sludge and filter cakes is treated schematically. Subsequently attention is paid to the changes taking place during filtration and expression, the major changes being those in local porosity inside flocs and between the flocs. For the description of the flow through a bed of permeable flocs a new, simple approximating model is proposed : the **"DUAL FLOW model"**. This allows the estimation of the effective permeability of a bed with permeable particles; from simulation follows that for compressed beds the contribution of the flow through the flocs can be much higher than that of the flow in the small open spaces between the flocs. Simulations of the expression of a floc indicate that during filtration and expression the local floc porosity will very fast reach equilibrium with the local compression pressure. From these considerations it follows that major focussing points for further study are :
- a more detailed insight into the relations between porosity, permeability and pressure distribution during filtration and expression
- theoretical and experimental insight in the size, strength and permeability of flocs, in dependence of structure parameters and pretreatment.

1. INTRODUCTION

I.1. General

In the beginning of 1990 we started a study of some fundamental aspects of sludge dewatering in our laboratory, within the larger Dutch national project "Municipal Waste Water Treatment 2000 (RWZI-2000)". A team of three full-time project members (ir. Arend J.M. Herwijn, ir. Erik J. La Heij, ing. Paul M.H. Janssen) took up the study in cooperation with dr.ir. W. Jan Coumans and myself. Basic aim of the study is the understanding of physical and physico-chemical phenomena occurring on microscale, and how these phenomena manifest themselves on the macrosopic scale. As desired results we see the links between various characterisation methods and physical parameters, and the development of theoretical and simulation models predicting filtration and expression behaviour. These type of models could then be used in the optimisation of dewatering processes and equipment parameters. One of the methods used in our study is the drying of filter cakes or parts, which gives fundamental insights in water transport and binding, but also gives information from which drying processes for sludge can be modelled and optimised.

As will become clear in the following an important element will be the colloid-chemical aspects of floc formation, strength and structure, and the consequences for the engineering aspects.

I.2. The presence of water

In Fig.1 we present schematically the way that water may be present in sludge and sludge cakes. In a suspension or in a filter cake we may distinguish a water phase and a floc phase. The porosity or volume fraction of the water phase is denoted by ε_b, and so the volume fraction of the flocs is equal to $(1 - \varepsilon_b)$.

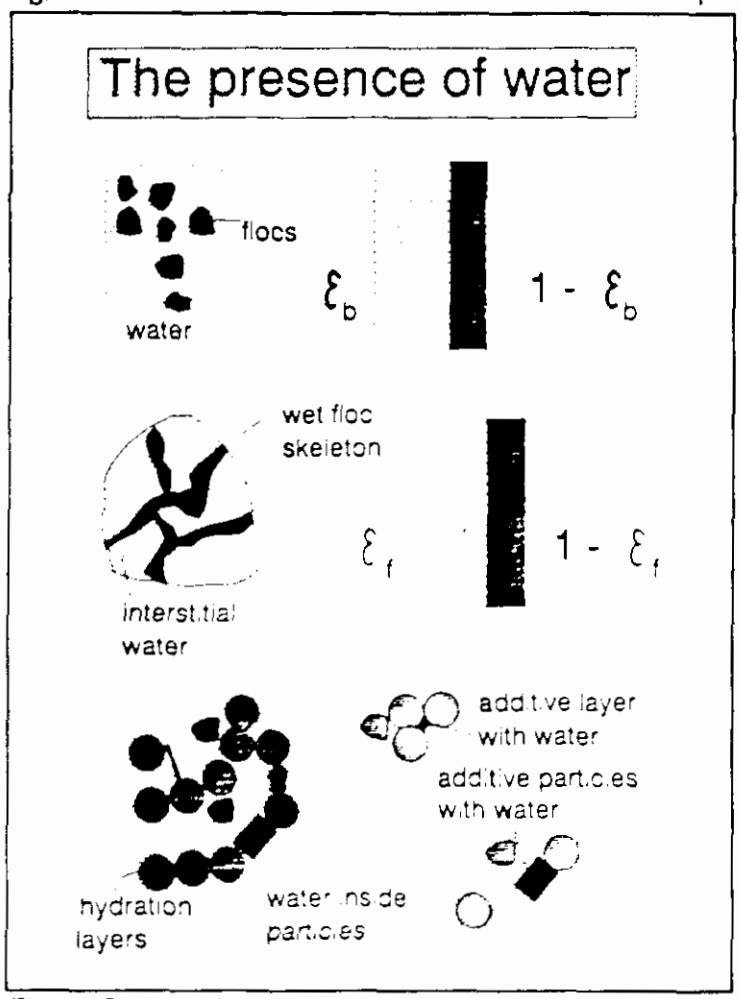


Fig. 1. Schematic representation of water in sludge

We also use the *void ratio* e_b, the volume of water phase per *unit of volume of floc phase* :

$$e_b = \frac{\varepsilon_b}{(1 - \varepsilon_b)} \qquad (1)$$

The flocs in turn consist of a wet skeleton, between which interstitial liquid is present in the floc pores. We have then the *internal floc porosity* ε_f, which is the fraction of the floc volume, taken up by the liquid. The volume fraction of the wet skeleton is thus $(1 - \varepsilon_f)$. The floc void ratio e_f is then given by :

$$e_f = \frac{\varepsilon_f}{(1 - \varepsilon_f)} \qquad (2)$$

Looking in more detail into the flocs we have a collection of *elementary particles*, made up of *basic sludge particles* and *additives*. The basic sludge particles stem from the waste water plant itself, and thus will vary with place, time of year, and other conditions. The additives are dependent on the specific sludge treatment given before solid-liquid separations. Now we have water inside the basic particles, like microbial cells, or pieces of wood,etc. Also we may have spots and/or particles of additives, which may contain water. Further we will have hydratation layers at the particle surfaces. For a quantitative account of the amount of water in the system, one should theoretically make a detailed mass balance of all substances in a sludge or filter cake. Although this is useful for scientific purposes, and also for a possible drying step, for the processes of filtration and expression we may reasonably approximate the water content of a system by :

$$X_{w,cake} = \frac{X_{w,i} + X_{add,1}\, X_{w,add} + \rho_l\, e_f\, (1 + e_b) / \rho_{sk}}{(1 + X_{add,1})} \qquad (3)$$

In this equation :

$X_{w,cake}$	= water content of cake	[kg/kg dry solids]
$X_{w,i}$	= internal water content of particles	[kg/kg dry solids]
$X_{add,1}$	= amount of dry additives/kg dry sludge, remaining in the sludge flocs	[kg/kg ds]
$X_{w,add}$	= water content of additive particles or layers	[kg/kg ds]
ρ_l	= density of water phase	[kg/m^3]
e_f	= floc void ratio	[m^3 liquid/m^3 ds]
e_b	= bed void ratio	[m^3 bed liquid/m^3 flocs]
ρ_{sk}	= density of (wet) floc skeleton	[kg/m^3]

I.3. Factors influencing dewatering steps

From the above picture we can derive several important factors, all influencing the dewatering process.

Floc formation

The flocs are formed from the basic sludge particles, in many cases with the addition of additives. Thus the nature of the basic sludge particles is one of the prime factors. This will depend on the treatment plant, the waste water stream fed, the conditions changing over time. The amount and nature of additives, combined with the way the process is carried out, is for a given set of basic sludge particles, at a given concentration determining for the floc formation process. This implies the way the floc skeleton is built up, the floc size, the initial floc porosity, the chain length of aggregates, the number of links per volume of floc, and the bond strength between the elementary floc particles.
Thus the floc formation process determines the ***initial floc porosity, size and strength.***
Examples of floc size distributions as measured in our lab by means of a Malvern Mastersizer are given in Figs. 2 and 3, with $FeCl_3/Ca(OH)_2$ and polyelectrolyte as additives. We see that with increasing addition of $FeCl_3$ up to a certain point the distribution tends to go to increasing size; for the polyelectrolyte this effect is much more markedly. Also interesting is the amounts of both additives needed to obtain an effect; for polyelectrolytes this is roughly 1/100 of that for the iron compound. It is clear that other mechanisms will be operating in both cases, and also that in the case of iron addition the iron hydroxide will form a considerable part of the sludge flocs.

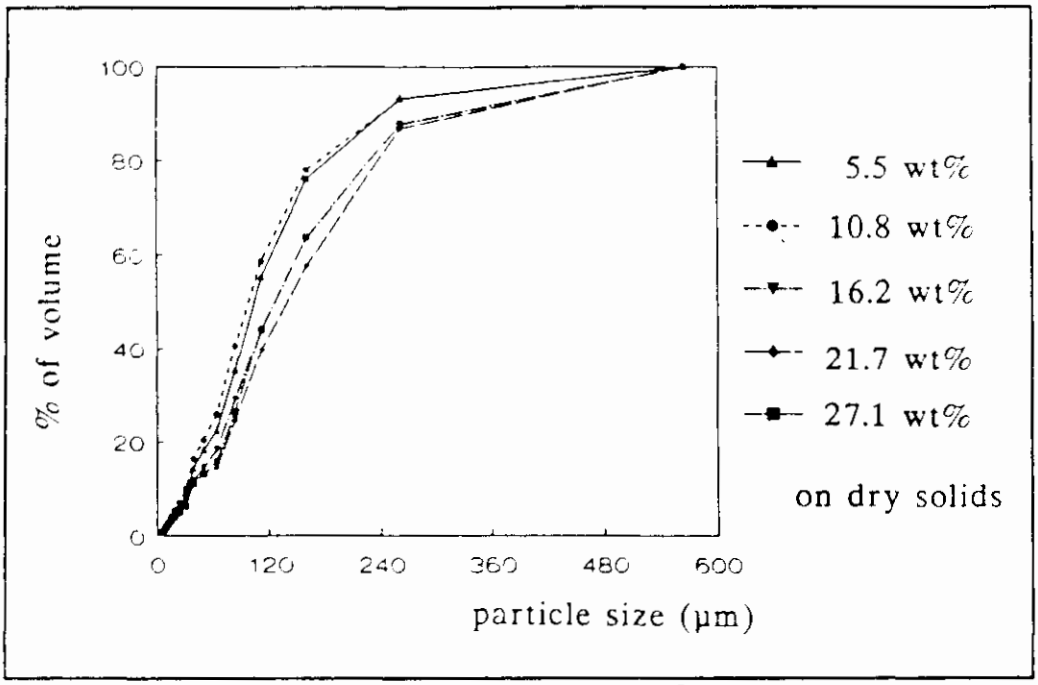


Fig. 2. Floc size distribution by flocculation with $FeCl_3$

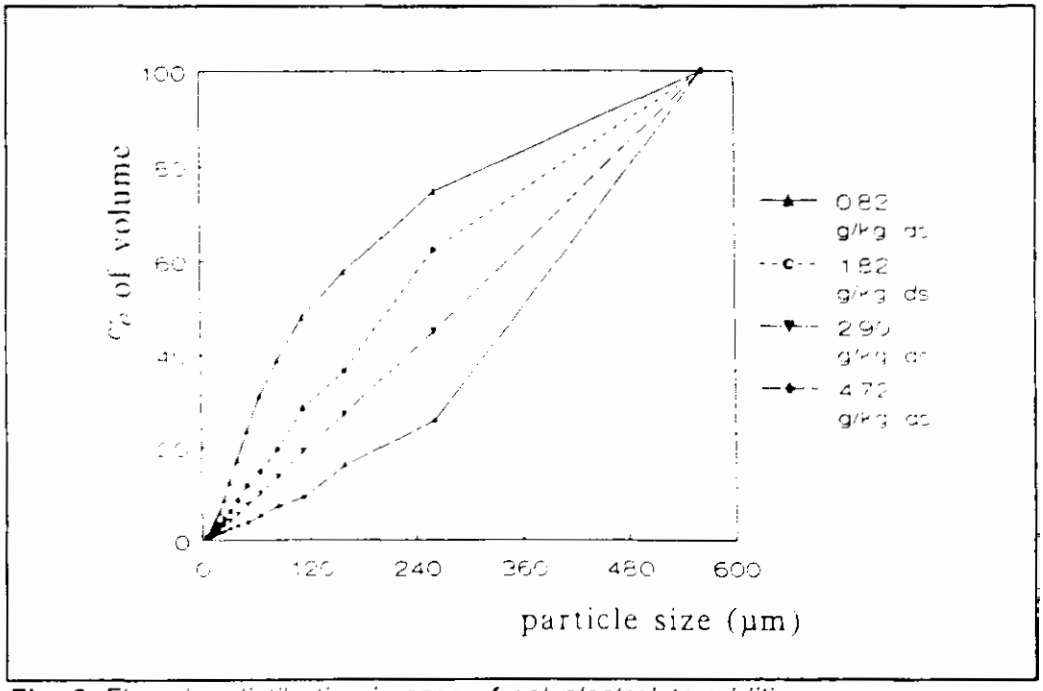


Fig. 3. Floc size distibution in case of polyelectrolyte addition

Dewatering

In general after a sedimentation step dewatering is performed by means of filtration, expression and in many cases drying. In filtration and expression the water phase moves relative to the solids under the influence of a gradient in liquid pressure. This can be represented by the following equations :

$$u_l = - \frac{K}{\eta} \frac{\partial p_l}{\partial z} = - \frac{1}{\eta R} \frac{\partial p_l}{\partial (z/L)} \qquad (4)$$

in which :

u_l	=	superficial liquid velocity	[m/s]
K	=	permeability	[m^2]
η	=	dynamic viscosity	[Pa.s]
p_l	=	liquid pressure	[Pa]
z	=	distance coordinate	[m]
R	=	filtration resistance of cake (= L/K)	[m^{-1}]
L	=	cake thickness	[m]

Often is also used the specific filtration resistance α :

$$\alpha = R / w \qquad (5)$$

with	α	=	specific filtration resistance	[m/kg]
	w	=	mass of cake per m^2 area	[kg/m^2]

We may write the relation between α and K by :

$$\alpha = \frac{1}{\rho_S (1 - \varepsilon) K} \qquad (6)$$

with	ρ_s	=	density of "bed particles"	[kg/m^3]
	ε	=	porosity	[-]

For the permeability we may write the Blake - Kozeny equation :

$$K = \frac{\varepsilon^3 d_p^2}{150 (1 - \varepsilon)^2} \qquad (7)$$

with	d_p	=	effective particle diameter	[m]

The conditions chosen in practice with regard to additives and filter aids reflect the search for a compromise : the material should filter well, which would mean a low

degree of deformation of flocs and beds, but on the other hand the final water content should be as low as possible, which means a considerable lowering of the porosity upon expression. This can be seen from Eq.(3), in which for a low deformable filter cake the main term in the numerator is that containing the void ratios: the major part of the water is present in the pores of the bed and in the interstitial pores inside the flocs.
During filtration there is a build-up of the cake, causing a conversion of liquid pressure into solid pressure, which tends to compress the cake. This compression can be viewed as a combination of simultaneous phenomena :
- expression and volume change of flocs
- bed compaction associated with floc deformation
- bed compaction associated with shear induced relative floc displacement

Next to the material properties of the flocs, also the choice of process conditions is determining the way the pressure profiles are built up. A higher filtration rate tends to increase the pressure gradients, thereby increasing the solid pressure on the particles, which in turn leads to a decrease in porosity and thus permeability K, which increases the pressure drop even more. At constant pressure filtration or expression, the resistance of the filter medium determines the initial flow rate and thereby also the steepness of pressure gradients in the initial phase of the process.

It is important to realise that it is the **combined effect of floc properties and process conditions**, which determines the filtration rate and/or pressure, and the final water content.

Although the description of filtration and expression requires a more detailed analysis, interesting observations for practice can be obtained from laboratory tests, such as filtration of a sample under constant pressure. By fitting the curve of filtrate volume over time, we find an average value of the specific cake resistance α_{av}. In Figs. 4 and 5 we see the influence of additives on this average resistance, again for the addition of $FeCl_3$, and for polyelectrolyte (Rohm KF-945), both at a filtration pressure of 2 bar.

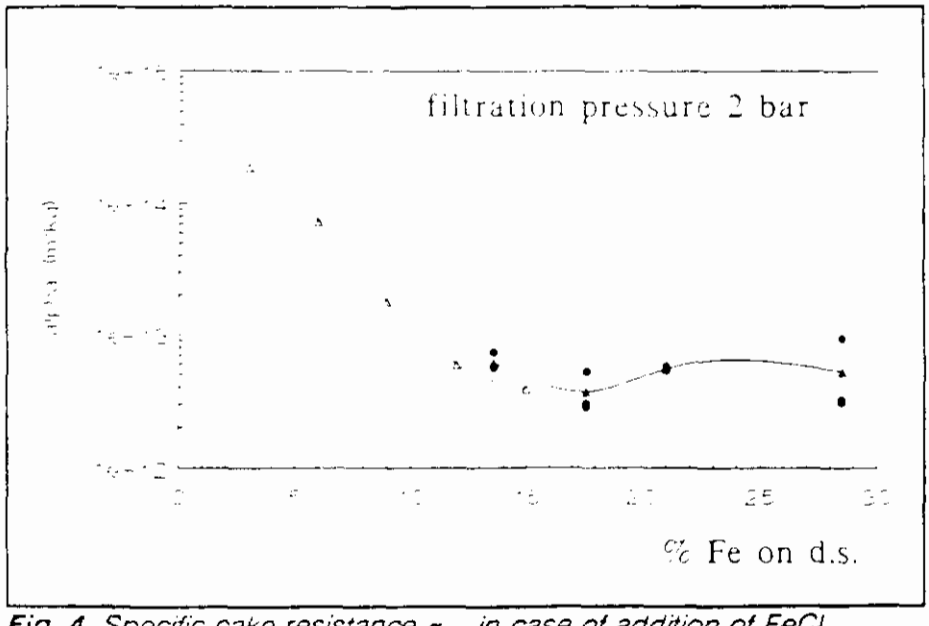


Fig. 4. Specific cake resistance α_{av} in case of addition of $FeCl_3$

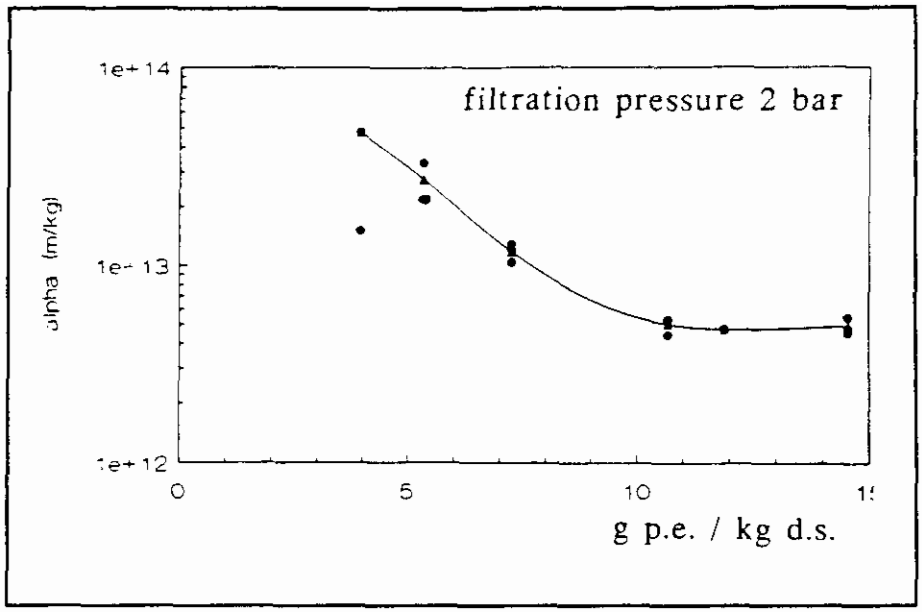


Fig. 5. *Specific cake resistance α_{av} in case of addition of polyelectrolyte*

It is clear that the resistance decreases upon addition up to a certain amount. The decrease is quite strong; comparison with the particle size data shows that there is no quantitative correspondence between the average particle size and the resistance. For $FeCl_3$ the effect is larger than expected from Eqs. (5) to (7), for polyelectrolyte it is lower. Apparently the deformation of the flocs and the bed under shear are also determining factors.
In Fig. 6 we have plotted the average specific cake resistance in dependence on the filtration pressure, which shows a typical power dependence with a power 0.8.

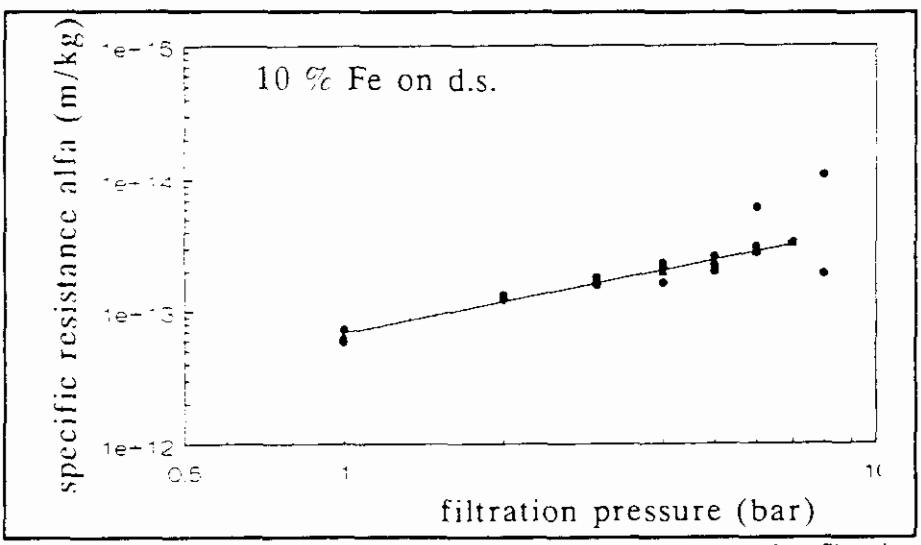


Fig. 6. *Dependence of the specific cake resistance on the filtration pressure, for addition of 10 % Fe on d.s.*

Although this and analogous tests give a practical insight into filtration and expression resistances, for treatment of more difficult situations, development of new

equipment and optimization, more detailed knowledge is required of the distribution of pressure and permeability over the material and of the development in the course of time.

2. SOME HYDRODYNAMIC CONSIDERATIONS

2.1. Flow through a bed of permeable flocs : the DUAL - FLOW model

In considering the modelling of the filtration process we were faced with the problem that the Blake - Kozeny equation for a bed was in principle derived for particles with a closed surface, and is based on the concept of the hydraulic radius of the pores in a bed, connected with the "wetted particle surface" [1]. Now it is known that flocs may have a quite open structure, and so an extension was sought of the theory. The basic assumption is that water flows both through the pores between flocs and through the flocs themselves. This has two effects for a given liquid pressure gradient :

- ***the liquid between the flocs is less decelerated at the floc surface***
- ***liquid flows through the flocs themselves***

From a simple approximation starting with laminar flow through a pore of which the walls are formed by porous flocs we can derive :

$$u_l = u_{l,bed} + u_{l,floc}$$

$$= \frac{1}{\eta} \left(- \frac{\partial p_l}{\partial z} \right) \left[\left(K_{b,sol} + \varepsilon_b K_f \right) + (1 - \varepsilon_b) K_f \right] \qquad (8)$$

$$= \frac{1}{\eta} \left(- \frac{\partial p_l}{\partial z} \right) \left[K_{b,sol} + K_f \right]$$

Herein $K_{b,sol}$ is the permeability of a bed consisting of particles of the same size as the flocs, but with a closed surface, and K_f is the permeability of the flocs. The K's are given by :

$$K_{b,sol} = \frac{\varepsilon_b^3 \, d_f^2}{150 \, (1 - \varepsilon_b)^2}$$

$$K_f = \frac{\varepsilon_f^3 \, d_e^2}{150 \, (1 - \varepsilon_f)^2} \qquad (9)$$

with d_f = floc diameter [m]
d_e = effective diameter of elementary floc particles [m]

For the effective permeability of the floc bed in relation to that of a similar bed consisting of closed particles we obtain :

$$\frac{K_{eff}}{K_{b,sol}} = 1 + \frac{\varepsilon_f^3}{(1-\varepsilon_f)^2} \frac{(1-\varepsilon_b)^2}{\varepsilon_b^3} \frac{d_e^2}{d_f^2} \qquad (10)$$

In order to estimate the importance of this effect we plotted in Fig. 7 this ratio vs. the bed porosity, for a floc porosity of 0.80, with the ratio of floc size to elementary particle size as parameter. We can see that for very high bed porosity there is hardly any influence, the bed behaves the same as for closed particles. For lower bed porosity, especially for $\varepsilon_b < 0.1$ we see that the flow through the flocs causes a large increase of the bed permeability, especially at decreasing floc size.

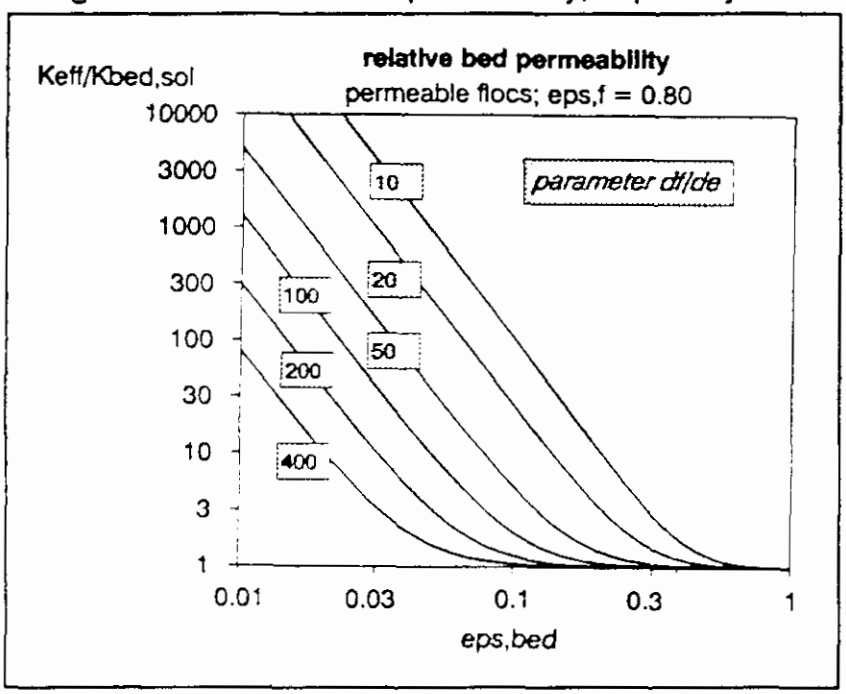


Fig. 7. Relative permeability of porous floc bed compared to closed particles, as function of bed porosity with relative floc size as parameter

Suppose that we can approximate the equilibrium void ratio of the flocs by :

$$e_f^* = e_{f0} (1 + a\, p_s)^{-\gamma_f (1 + e_{f0})} \qquad (11)$$

with	$e_{f,0}$	= initial floc void ratio	[-]
	p_s	= solid pressure	[Pa]
	a	= coefficient	[Pa^{-1}]
	γ_f	= floc compression coefficient	[-]

In this hypothetical relationship is reflected that a more open floc will be weaker. Now for a bed we may assume that a small deformation and displacement of flocs causes a much larger change in bed porosity than in floc porosity :

$$\frac{e_b}{e_{b,0}} = \left(\frac{e_f}{e_{f,0}}\right)^{\beta} \qquad (12)$$

with β = bed compression exponent (>1) [-]

In Fig.8 the simulated effects of the compression pressure on the porosity of the flocs and of the bed is shown.

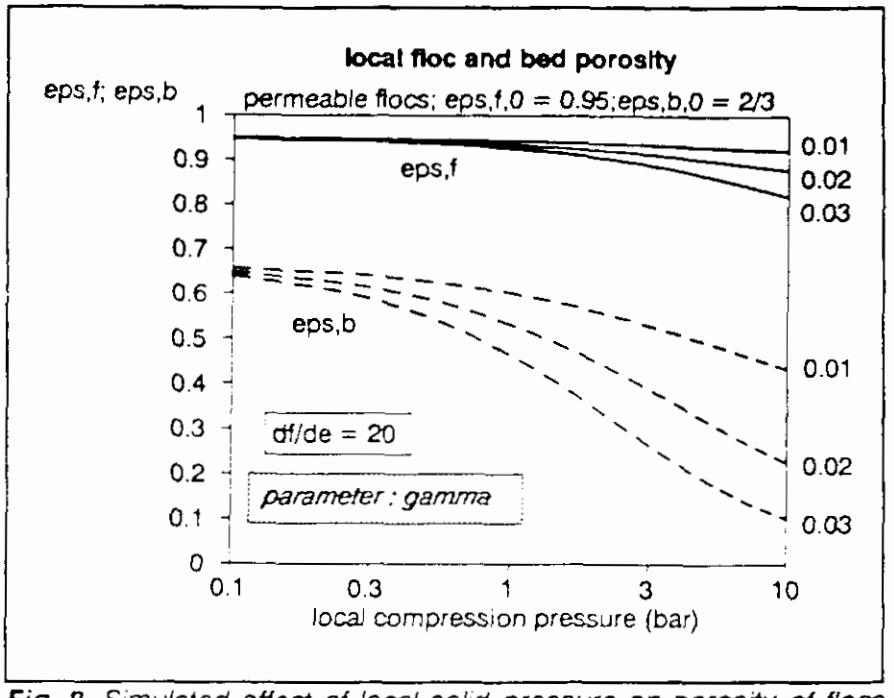


Fig. 8. Simulated effect of local solid pressure on porosity of flocs and of bed.

In Fig.9 the permeability of the bed with porous flocs is now compared with the initial permeability, for different local (uniform) solid pressures. The dotted lines represent the change in permeability of the spaces between the flocs, the drawn lines show the permeability through the whole bed. It is again clear that for the small flocs considered in this simulation a considerable amount of the total flow goes through the flocs. Also a considerable decrease is seen of the bed permeability with increasing pressure.

In Fig.10 again the relative permeability is plotted vs. the compression pressure, but now for larger flocs. We now see that the difference between a bed of flocs and a bed of closed particles is considerably less; the contribution of floc flow is here relatively low. This leads however to a much stronger decrease in overall permeability than in the case of smaller flocs.

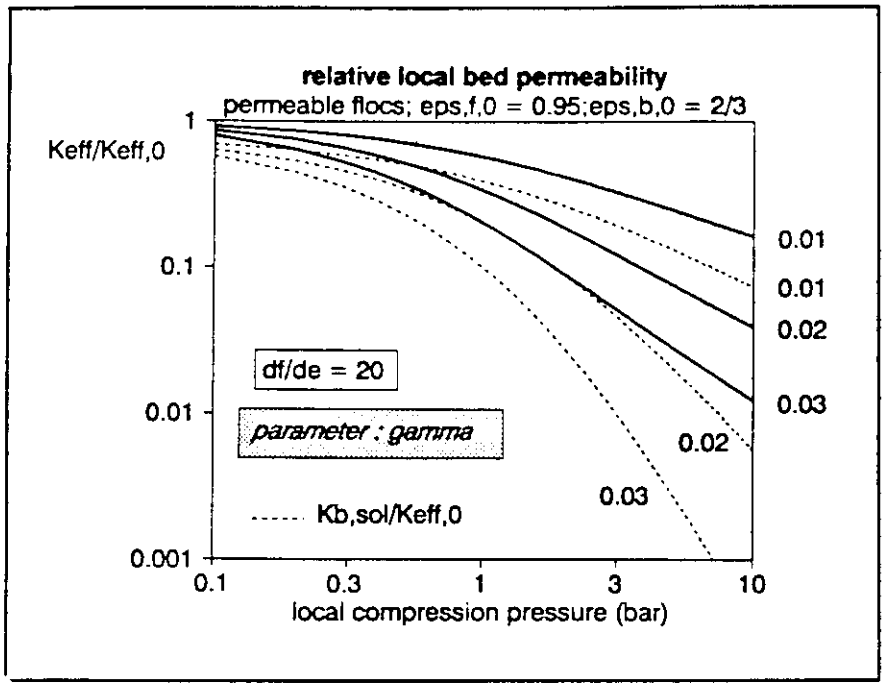


Fig. 9. Simulated effect of solid pressure on permeability of a bed of porous flocs. Small floc size.

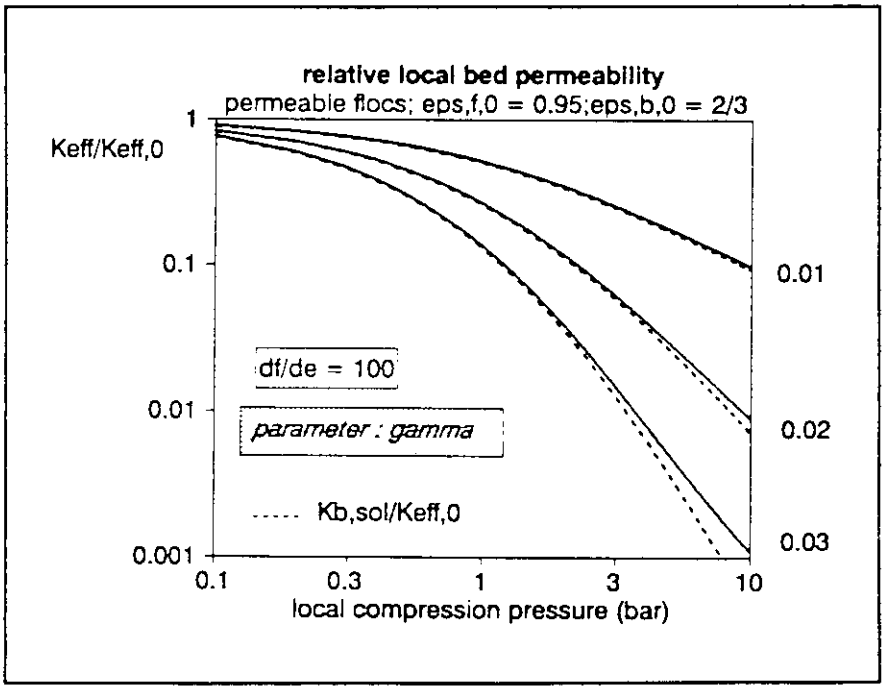


Fig. 10. Influence of the solid pressure on permeability of a floc bed. Larger flocs.

In conclusion we may state that this model is a good base for further refinement and experimental study. It will be especially of interest to investigate the separate deformations and porosity changes of flocs and beds, and the changes this brings

in overall permeability.

2.2. Dynamic flow through compressible beds; application to floc expression

2.2.1. Description of theory

The theory of dynamic changes in pressure and porosity profiles during filtration and expression has been reported by several authors [2-4]. The basic equation for the porosity change in one-dimensional flow reads :

$$\frac{\partial \varepsilon}{\partial t} = - \frac{\partial}{\partial r}(u_l) \qquad (13)$$

Herein r is the distance coordinate with respect to a fixed coordinate system.
We assume a modified version of D'Arcy 's law :

$$v_l - v_s = - \frac{K_f}{\eta \varepsilon} \left(\frac{\partial p_l}{\partial r} \right) \qquad (14)$$

with v_l = *linear* liquid velocity [m/s]
v_s = *linear* velocity of solids [m/s]

The relation between the linear and superficial velocities reads :

$$v_l = \frac{u_l}{\varepsilon}$$

$$v_s = \frac{u_s}{(1 - \varepsilon)} \qquad (15)$$

Assuming no net volume production we have :

$$u_l + u_s = u_t = f(r) \qquad (16)$$

Herein u_t is the total net convective flow per m^2, which for filtration is equal to the filtrate flow per m^2, and for expression is equal to 0.
Neglecting gravity terms we have for the force balance :

$$p_l + p_s = p_t$$

$$\frac{\partial p_l}{\partial r} = - \frac{\partial p_s}{\partial r} \qquad (17)$$

Combination of Eqs.(13) - (17) leads to the differential equation :

$$\frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial r}\left(- u_t\, \varepsilon - (1 - \varepsilon)\, \frac{K_f}{\eta}\, \frac{\partial \varepsilon}{\partial r} \Big/ \frac{\partial \varepsilon}{\partial p_s} \right) \qquad (18)$$

in which it is assumed that there is a unique relation between ε and p_s.

The boundary conditions depend on the type of operation. For filtration we have :

$$r = 0 \qquad - u_l = R_m\, (p_{l,r=0} - p_0)$$
$$r = R(t) \qquad \varepsilon = \varepsilon_0 \qquad (19)$$

with R_m = resistance of filter medium [m /Pa/s]
$r = 0$ place of filter medium
$R(t)$ = coordinate of cake front [m]

For the case of expression we have :

$$r = 0 \qquad \frac{\partial \varepsilon}{\partial r} = 0$$
$$r = R(t) \qquad \varepsilon = \varepsilon^* \qquad (20)$$

with $r = 0$ coordinate of impermeable surface or of symmetry plane
$R(t)$ = coordinate of expression front [m]
ε^* = porosity in equilibrium with applied solid pressure [-]

The latter boundary conditions apply when the resistance of the medium with which pressure is applied is very low. In case there is a considerable resistance, a condition similar to Eq.(19) should be applied.

Solution of the differential equation can only be done numerically. Before doing that however a change of coordinates is necessary, taking the solids volume or mass as measure.

2.2.2. Application to expression of a sludge floc

As follows from the considerations of the DUAL FLOW model, for a theoretical description of a filtration or expression process of a bed one should know the changes both in bed and in floc porosity. Therefore it was thought interesting to model the expression of a floc. The system considered is that of a flat floc, which has a thickness 2 R_f, and is expressed symmetrically in the r-direction. The equations of 2.2.1. were transformed to solids volume coordinates, and a modified Crank-Nicholson finite difference scheme was used to solve the equations. For the effect of solid pressure on the equilibrium void ratio Eq.(11) was used. In Fig.11 the calculated porosity profiles for a floc with an initial thickness of 200 μm are given. Initially there is a very steep gradient at the expression surface, but in progress of

time the porosity profile penetrates into the heart of the floc.

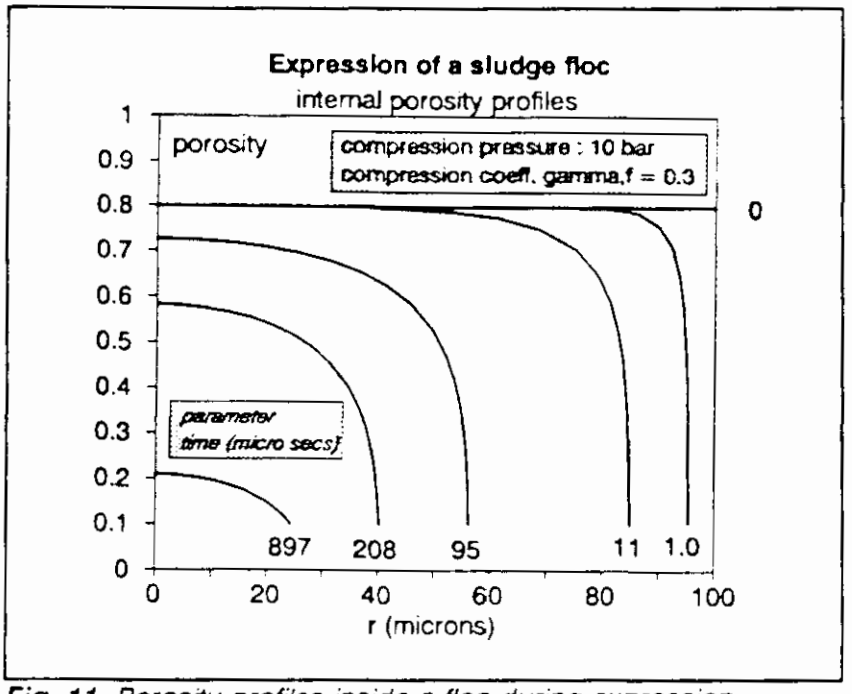


Fig. 11. Porosity profiles inside a floc during expression

In Fig. 12 we see the profiles of the solid pressure as this penetrates into the floc. we see that the pressure profile remains very steep near the floc surface, and only relaxes in the last phase of the expression.

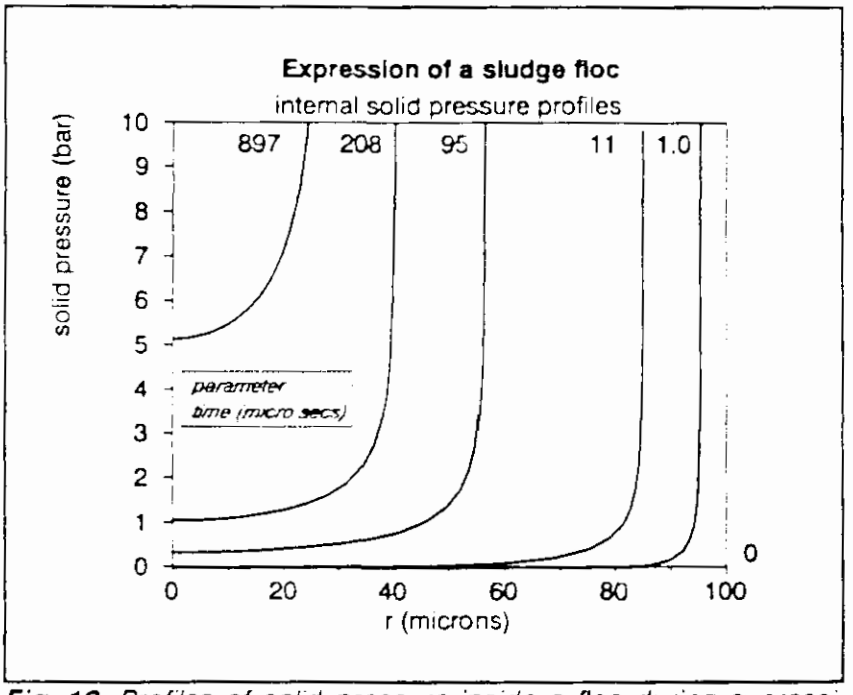


Fig. 12. Profiles of solid pressure inside a floc during expression.

In Fig.13 the average porosity of the floc is given vs the expression time. We see that for this case the largest part of the expression takes place within 1 ms. From this, and other simulations we conclude that within a larger scale filtration or

expression the local floc porosity may be considered to reach equilibrium with the local compression pressure within a very short time.

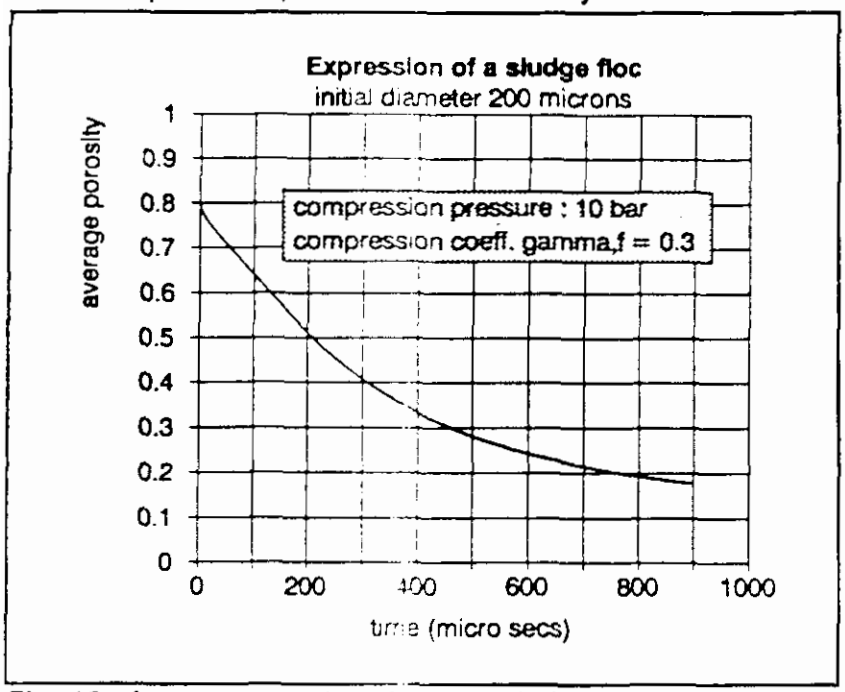


Fig. 13. Average porosity of a floc during expression in the course of time.

3. ELEMENTS OF FURTHER RESEARCH

3.1. Experimental

The general target for further experimental work may be formulated as :

obtaining insight into the relation between composition, treatment and physical properties of flocs and cakes.

As follows from the various considerations given above we may see as important physical properties :

1. Particle size distribution and particle morphology

These represent the initial conditions of the flocs as they enter the dewatering process. Next to laser-diffraction equipment also analysis of optical images and electron microscopy are important to get impressions of irregularities in shape, and of structural aspects.

2. Physico-chemical aspects

It is of great importance to lay the relation between the various factors influencing floc formation and the floc size, strength and structure. This means that measurements should include zeta-potential measurements for various additives, the measurements under 1. and rheological measurements. Important is also to study the properties in relation to different floc preparation methods. Maybe special methods should be devised to measure floc strength directly.

3. Water binding and transport

Since water may be present in various ways, it is of interest to determine the

amounts. This may for a part be done by indirect methods. Experiments on freezing curves and the determination of water vapour sorption isotherms may provide information on the amounts of free and bound water. Drying experiments of filter cakes may be analysed in terms of the effective diffusion coefficient, which is related to the pore size distribution [5]. An example of some typical drying curves is given in Fig.14. The upper curve is for the more open part of a cake, the lower one for a sample near the filter. It is clear that the drying rate is influenced strongly by the differences in compression. Drying experiments thus offer a possibility of obtaining insight into the pore sizes and the liquid flow for cakes with different histories. Of course the information is also needed to design and optimize drying equipment.

4. Macroscopic water transport and filtration properties

A systematic investigation is needed into porosity, permeability and deformation of flocs and beds, as influenced by the initial floc properties and the process variables. One aspect is to carry out standard tests, such as the Capillary Suction Time, the (Modified) Filtration test. However for better understanding special experimental methods have to be devised to measure properties of cakes under homogeneous pressure conditions. Also it should be verified whether indeed the rate-controlling factor for cake and floc deformation is the time needed for water displacement, or whether purely mechanical properties may also play a role. Experimental investigation of the DUAL FLOW model could be done with model systems.

5. Filtration and expression rate

In order to verify more fundamental models, of course filtration and expression experiments under various process conditions should be performed, both in dedicated laboratory equipment and in well-instrumented practical scale equipment.

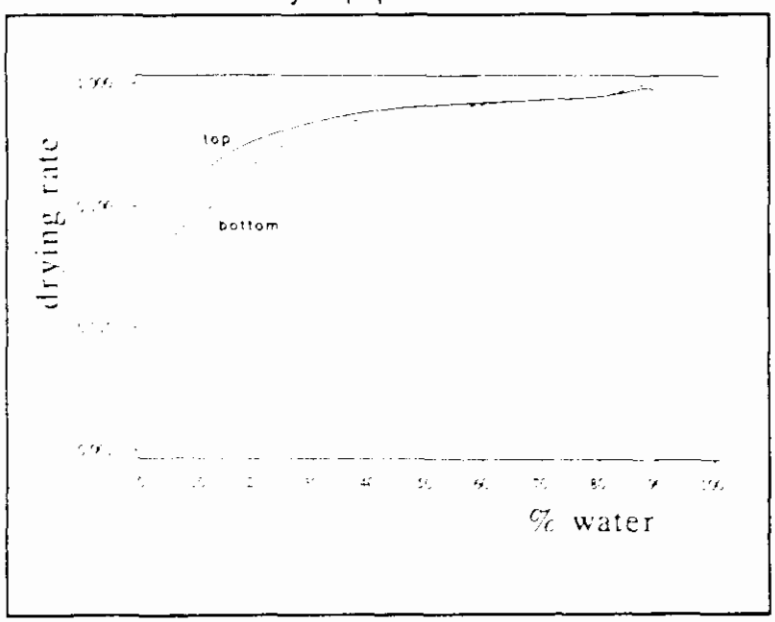


Fig. 14. Drying curves of different parts of a filter cake

3.2. Theoretical modelling

□ The DUAL FLOW model must be tested and possibly refined.
□ For the description of filtration and expression dynamics also the transport through the flocs should be accounted for.

□ As in reality filtration is not a one-dimensional process, a model should be formulated for the transport and deformation in 2- and 3-dimensional situations.
□ Models for the strength of flocs as dependent on structure may be set up, as related to efforts in food and polymer technology.
□ Models for the analysis of drying experiments will provide insight into the liquid motion in small pores.
□ For the various standard tests more detailed models must be made in order to relate the macroscopic outcome to local properties and dynamics.
□ Models for the binding of water must be compared with the outcome of freezing and sorption isotherm experiments.
□ Equipment models must finally be made for the description of large scale dewatering. These models can then be used for analysis of existing situations and as a simulation tool for the definition of process conditions or the design of new equipment.

4. FINAL REMARKS

Although considerable work has been carried out in the past, it is clear that on the fundamental side still a lot is to be done. As some new elements in this paper the DUAL-FLOW model was introduced, and a consideration of the expression of a floc.
In the framework as sketched here I think it is possible to make a link between all kinds of tests, fundamental properties, and theoretical descriptions for practical dewatering processes. This will lead to a much larger predictability of these processes, and combined with the insight from the physico-chemical effects to practical solutions in difficult situations.

References

1. Bird, R.B., Stewart,W.E. & Lightfoot, E.N., "*Transport Phenomena*", Wiley, 1960
2. Tiller,F.M. & Shirato,M., "The Role of Porosity in Filtration: VI. New Definition of Filtration Resistance", *AIChEJ*, **10** (1), 61 - 67, 1964
3. Shirato, M., Sambuichi,M., Kato, H. & Aragaki, T., "Internal Flow Mechanism in Filter Cakes, AIChEJ, **15** (3), 405 - 409, 1969
4. Wakeman, R.J., "A numerical integration of the differential equations describing the formation of and the flow in compressible filter cakes", TransIChemE, **56**, 258 - 265, 1978
5. Krischer, O. & Kast, W., "*Die wissenschaftlichen Grundlagen der Trocknungstechnik*", 3d ed., Springer, 1978

FILTRATION AND EXPRESSION OF SEWAGE SLUDGE

E.J. La Heij, A.J.M. Herwijn, W.J. Coumans and P.J.A.M. Kerkhof.
Department of Chemical Engineering, Laboratory for Chemical Process Technology, FT-hal, 5600 MB, P.O. Box 513, Eindhoven University of Technology, Eindhoven, The Netherlands.

Filtration and expression behaviour of sewage sludges are studied with batchwise filtration/expression equipment and the compression-permeability cell. Because there are porosity gradients in the filter cake which change continuously during time, flow rate equations, stress balances, constitutive equations and continuity equations are used to model the filtration- and expression phase. The filtration- and expression phase are modelled with elastic material deformation and compared with experiments.

INTRODUCTION

After biochemical treatment, sewage sludge needs to be dewatered. Mostly the dewatered sludge is used directly for agriculture. However due to severe legislation incineration is more and more demanded. That means to reduce energy costs, it is desirable to remove the maximum feasible amount by the dewatering stages. The dewatering stages are filtration and expression which are normally carried out in filter presses and belt presses and to some extent decanter centrifuges. Final average dry solids contents are about 25-35 wt% for filter presses and 16-24 wt% for belt presses. These data include flocculants. Flocculants are used to improve the dewatering behaviour. In the Netherlands mostly $FeCl_3$ in combination with $Ca(OH)_2$ for filter presses and highly cationogenic polymers for belt presses are used. Getting more insight into the physical and physico-chemical processes involved in these sludge dewatering processes can help to improve the dewatering characteristics of existing techniques. A study of fundamental aspects of sludge dewatering is carried out at our laboratory, within the larger Dutch research program entitled "Future Treatment for Municipal Waste Water, RWZI 2000". Mathematical modelling and developing design and optimization rules of process conditions is of great importance to understand fundamental aspects and to predict final average porosities (final dry solids contents) and dewatering times. To simulate the filtration and expression operations we used a compression-permeability (C-P) cell to obtain permeabilities and compressibility coefficients. Numerical calculations based on these values are then compared with batchwise filtration/drainage and expression experiments.

DESCRIPTION OF THE FILTRATION- AND EXPRESSION PROCESS

To model the filtration- and expression behaviour of sewage sludge, attention must be focused on flow through compressible cakes. Therefore we need flow rate equations, stress balances, constitutive equations and continuity equations. For the flow rate equation the Darcy-Shirato equation is used which takes into account that there is also solids movement. The constitutive equations describe the relation between porosity, specific cake resistance, permeability and the compressive

---

Eindhoven University of Technology,
Eindhoven, The Netherlands.

pressure.
We used the following empirical power functions [5] :

$$\varepsilon = \varepsilon_0 \left(1 - p_s / p_{s0}\right)^{-\lambda} \qquad (1)$$

$$K = K_0 \left(1 - p_s / p_{s0}\right)^{-\delta} \qquad (2)$$

where

ε = local porosity, [-]
K = local permeability, [m²]
p_s = compressive pressure, [Pa]
p_{s0} = constant, [Pa]
λ, δ = compressibility coefficients, [-]

ε_0 and K_0 are the porosity and permeability respectively at zero compressive pressure p_s=0. These relations are determined with the C-P cell.

Combination of the flow rate equation, the stress balance, the constitutive equations and the continuity equations leads to the following partial differential equation (convection-diffusion type)[1] , which describes the change of the porosity in time and place in a filter cake:

$$\frac{\partial \varepsilon}{\partial t} = u_{lm} \frac{\partial \varepsilon}{\partial x} + \frac{\partial}{\partial x}\left[\frac{K}{\eta}(1-\varepsilon)(\rho_s - \rho_l) g - \frac{dp_s}{d\varepsilon}\frac{\partial \varepsilon}{\partial x}\right] \qquad (3)$$

t = time , [s]
η = viscosity filtrate, [Pa s]
ρ_s = density solids, [kg m⁻³]
ρ_l = density filtrate, [kg m⁻³]
g = gravity acceleration, [m s⁻²]
u_m = superficial liquid velocity through filtermedium, [m s⁻¹]

Because during both filtration and expression the cake structure changes continuously, a direct solution of equation [3] is not useful. Therefore transformation to solid based or non-dimensional coordinates is needed. Filtration is a process where a cake builds up, we therefore need a moving boundary condition. If we have a cake which is drained with fluid, we call it drainage and we may change equation [3] into a solids based coordinate ω:

$$\omega = \int_0^x (1-\varepsilon)\, dx \qquad (4)$$

Transformation of equation [3] into a solids based coordinate and void ratio e ($\varepsilon/\varepsilon_s$) leads to:

$$\frac{\partial e}{\partial t} = \frac{\partial}{\partial \omega}\left[\frac{K}{\eta}\frac{1}{1-e}(\rho_s - \rho_l) g - \frac{dp_s}{de}\frac{\partial e}{\partial \omega}\right] \qquad (5)$$

with initial condition for filtration:

$$e = e_0 \qquad \text{at } t = 0 \qquad (6)$$

boundary conditions for filtration:

$$e = e_0 \qquad \text{at } \omega = \omega_{max} \quad t > 0 \qquad (7)$$

$$u_{lm} = \frac{K_m}{\Delta x_m \eta}\left(p - p_{s,\omega=0}\right) \qquad \text{at } \omega = \omega_0 \quad t > 0 \qquad (8)$$

where

K_m = permeability filtermedium, [m²]
Δx = thickness filtermedium, [m]
$p_{s,\omega=0}$ = compressive pressure at filtermedium, [Pa]

The initial condition for the expression phase will be determined by the porosity/void ratio profile at the end of the filtration phase.
Boundary conditions for expression:

$$\frac{\partial e}{\partial \omega} = 0 \qquad \text{at } \omega = \omega_{max} \quad t > 0 \qquad (9)$$

$$e = e(p_{(s,\omega=0)}) \qquad \text{at } \omega = 0 \quad t > 0 \qquad (10)$$

The void ratio or porosity near the filter-medium will remain constant during expression and is determined at the end of the filtration phase. The void ratio/porosity, hydraulic and compressive pressure at the top of the cake will change continuously.

With equation (4) we can calculate porosity, compressive-, hydraulic pressure profiles, the cake height and the superficial liquid velocity as a function of time. With a drainage and expression cell we can measure the cake height and superficial liquid velocity as a function of time.

In the derivation of the above mentioned equations, we made one important assumption: the porosity ε is solely a function of the compressive pressure p_s . This means the solid skeleton behaves elastic; it deforms instantaneously at a given stress. I there is a time lag to deform the solid skeleton, the solids behave viscous; this can be either visco-elastic or visco-plastic.

EXPERIMENTAL

In figure 1 a schematic diagram of the used filtration/expression and drainage device (inner diameter 8 cm) is given. The outcoming filtrate is collected on a balance and the data are transmitted to a computer which registrates time and filtrate-volume. Before carrying out a drainage experiment, a slurry of sewage sludge is placed in the cell and water flows out under gravity forces until a cake is formed. Thereafter a liquid layer is placed on top of the cake (see figure 1) and air pressure will finally determine the drainage pressure. For expression experiments, a closed piston is placed on top of the formed cake.

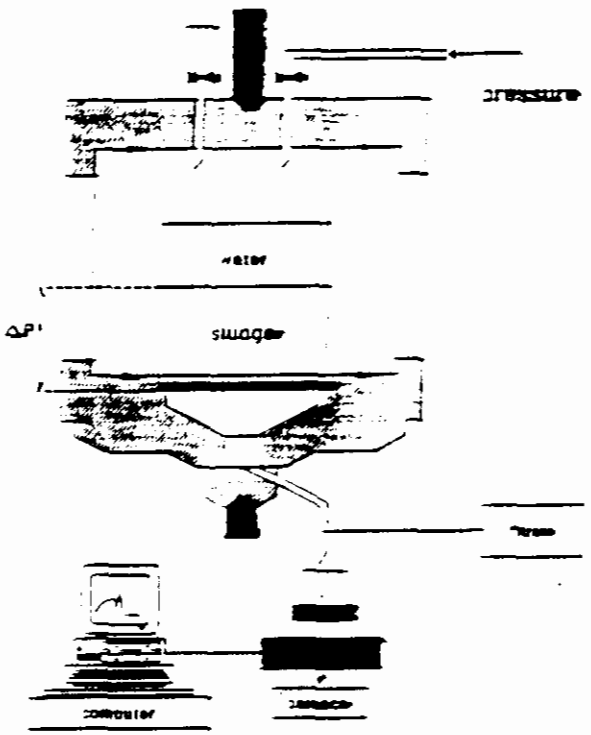


Figure 1. Schematic diagram of filtration/drainage/expression device.

RESULTS

In figure 2 the superficial liquid velocity u_m versus time for a drainage experiment is given for a sludge flocculated with 11 wt% $FeCl_3$/20 wt% Ca(OH) on dry solids basis. On the basis of C-P measurements, results of numerical calculations with elastic material properties are shown in figure 3. It can be seen that there is a discrepancy between measured and calculated time scales. (the shape of the curves however is the same). Calculations showed that with increased medium resistance during filtration (in the model the medium resistance was assumed to be constant) the time scale extended only a few seconds and could not explain the discrepancy between

measured and calculated times. Therefore this difference must be due to the fact that the porosity ε is not solely a function of the compressive pressure p_s. There is some time lag which implicates visco-elastic or visco-plastic material behaviour.

In figure 4 the average porosity of an expression experiment with a sludge flocculated with 6 wt% $FeCl_3$/20 wt% $Ca(OH)_2$ is shown. The final equilibrium condition, uniform porosity profile, is still not reached after two hours. In figure 5 the calculated porosity profiles based on elastic material properties of the expression experiment are shown. The uniform porosity profile is already reached after ± 10 minutes.

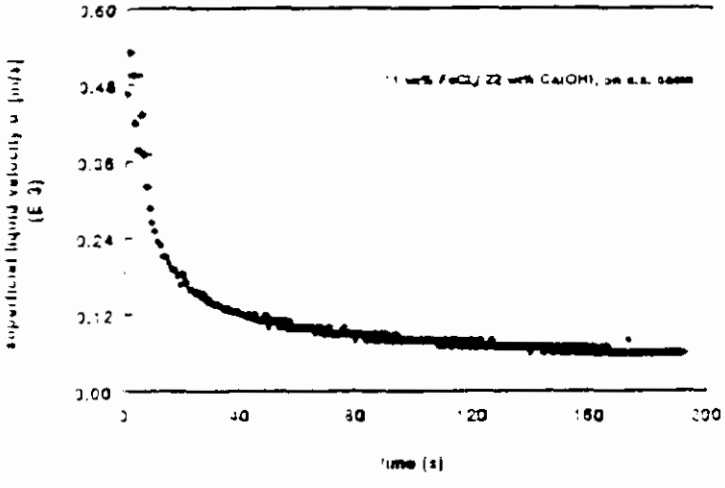


Figure 2. Superficial liquid velocity u_{sl} versus time, drainage experiment (sludge flocculated with 11 wt% FeCl, and 20 wt% Ca(OH)$_2$ on dry solids basis; Δp=40 kPa).

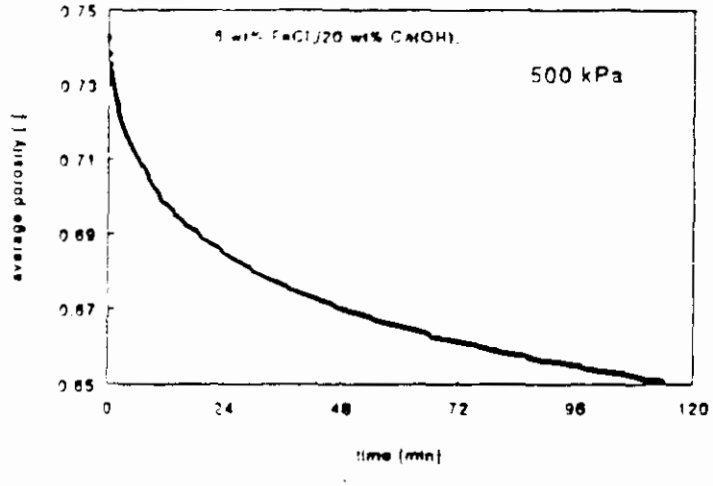


Figure 4. Average porosity versus time, expression experiment (sludge flocculated with 6 wt% FeCl, and 20 wt% Ca(OH)$_2$ on dry solids basis; Δp=500 kPa).

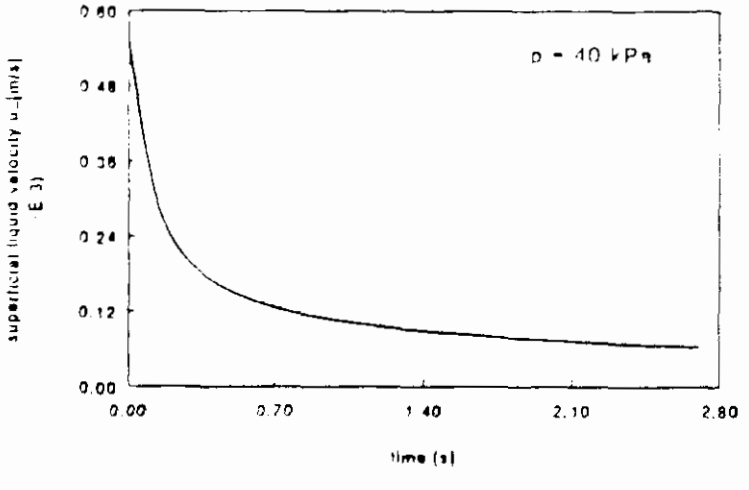


Figure 3. Calculated superficial liquid velocity versus time; elastic material properties.

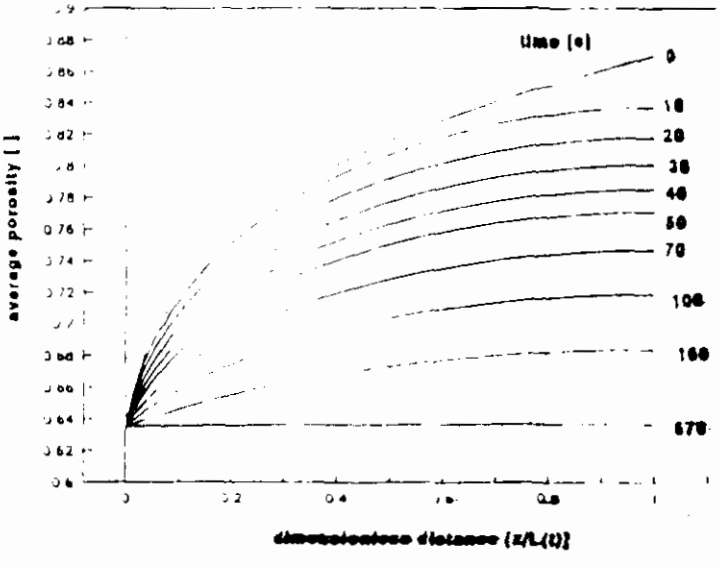


Figure 5. Calculated porosity profiles during expression phase; ΔP=500 kPa.

This implies that there is visco-elastic or visco-plastic material behaviour during both the drainage and the expression phase. Shirato et al.[3] investigated the visco-elasticity of clay suspensions with a Kelvin-Voigt model for only the expression phase and used analytical solutions. To determine the elastic modulus E and the viscosity of the solids skeleton η_s a constant stress tensor (compressive pressure) is needed. However, because there are always pressure profiles in the cake during filtration/drainage and expression experiments, it is very difficult to obtain E and η_s. Therefore simple solutions to obtain elastic moduli and viscosities of rheological models (e.g. the Kelvin-Voigt model) must be sought.

Flocculants have great influence on the dewatering behaviour. Not only on the liquid flow resistance but also on the visco-elasticity. In figure 6 the effect of the concentration $FeCl_3$ on the average specific cake resistance α_w [m/kg] is shown. This α_w includes liquid flow and the visco-elasticity of the solids skeleton. For $FeCl_3$ this kind of curves can often be found. For sludge flocculated with polyelectrolytes often an optimum can be found. Measurements with the C-P cell showed that there was hardly any change in the specific cake resistance when the flocculant dosage was increased. However filtration experiments showed an important change in α_w. Therefore the measured α_w during a filtration experiment is often a sum of liquid flow resistance and visco-elasticity/plasticity.

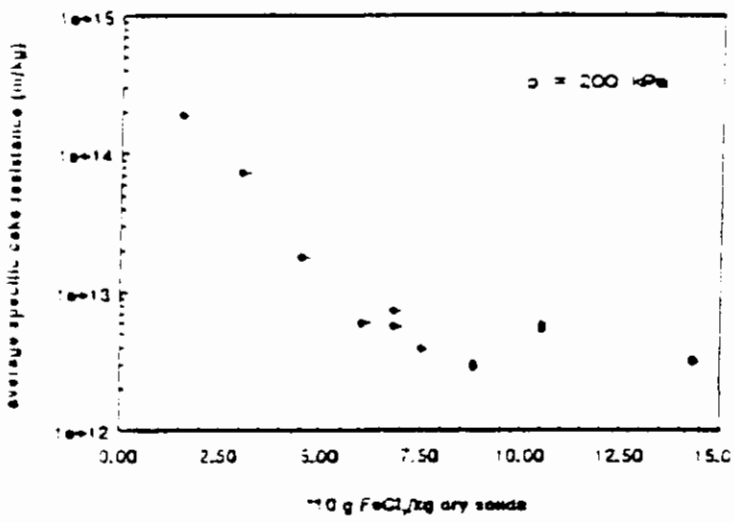


Figure 6. Specific cake resistance α_w versus dosage $FeCl_3$ (on dry solids basis).

SUMMARY AND CONCLUSIONS

Numerical calculations based on elastic material properties show discrepancies between model and experiment. This is for both the drainage- and expression phase. The equilibrium condition after drainage (hydraulic pressure at filtermedium equals zero) and after expression (hydraulic pressure through all the cake equals zero, uniform porosity profile) establishes very slowly. This implies that we need to model the filtration/drainage- and expression phase with visco-elastic or visco-plastic material deformation and that it will take long dewatering times to reach high final dry solids contents.

Further, flocculants have great influence on the dewatering time. Optimum conditions lead to low cake resistance and low visco-elastic material deformation.

NOTATION

e	void ratio	[-]
E	elastic modulus	[Pa]
g	gravity acceleration	[m s^{-2}]
k	permeability	[m^2]
k_0	permeability at p_s=0	[m^2]
k_m	medium permeability	[m^2]
p	applied filtration or expression pressure	[Pa]
p_l	hydraulic pressure	[Pa]
p_s	compressive pressure	[Pa]
$p_{s,\omega=0}$	compressive pressure at ω=0	[Pa]
p_a	constant	[Pa]
t	time	[s]
u_l	superficial liquid velocity	[m s^{-1}]
u_{lm}	superficial liquid velocity through filtermedium	[m s^{-1}]
z	distance in cake between 0 and H(t)	[m]
Δx	thickness filtermedium	[m]

Greek symbols

α_w	average specific cake resistance during filtration exp.	[m kg^{-1}]
ε	porosity	[-]
ε_0	porosity at p_s=0	[-]
ε_s	solidosity	[-]
β	compressibility coefficient	[-]
η_l	viscosity filtrate	[Pa s]
η_s	viscosity solids skeleton	[Pa s]
λ	compressibility coefficient	[-]
ρ_l	density filtrate	[kg m^{-3}]
ρ_s	density solids	[kg m^{-3}]
ω	solids material coordinate	[m]
ω_{max}	maximum solids coordinate	[m]

LITERATURE CITED

1) La Heij, E.J.
Compressible cake filtration: an overview
Internal report, Eindhoven University of Technology, The Netherlands, 1991

2) Shirato M. et al.
Internal flow mechanisms in filter cakes
A.I.Ch.E., J., vol.15, no.3, 1969

3) Shirato, M., Murase, T., Iwata, M., Nakatsuka, S.
The Terzaghi-Voigt combined model for constant pressure consolidation of filter cakes and homogeneous semi-solid materials
Chem. Eng. Science, vol.41, no.12, 1986

4) Stamatakis, K., Tien, C.
Cake formation and growth in cake filtration
Chem. Eng. Science, vol.46, no.8, 1991

5) Tiller, F.M., Yeh, C.S.
The role of porosity in filtration part XI: Filtration followed by expression
A.I.Ch.E., J., vol.33, no.8, 1987

Acknowledgement

This work is financially supported by the "Institute of Inland Water Management and Waste Water Treatment (RIZA)" and the "Foundation for Applied Waste Water Research (STORA)" in the Netherlands.

THE SOLID-WATER BOND STRENGTH IN SEWAGE SLUDGE

A.J.M. Herwijn, D.Q.A. van Dijke, E.J. La Heij, W.J. Coumans and P.J.A.M. Kerkhof.
Department of Chemical Engineering, Laboratory for Chemical Process Technology, FT-hal, P.O. Box 513, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands.

The solid-water bond strength in sewage sludge has been studied with two different techniques: thermal analysis and water vapour sorption isotherms. The bond enthalpy as a function of the sludge cake moisture content provides information on the maximum feasible dry solids content in a filtration process. In this contribution some preliminary results will be presented.

INTRODUCTION

Disposal of (dewatered) sewage sludge on dumping sites and in agriculture is becoming more restricted to severe legislation. Disposal options that are of interest now are combustion and drying of dewatered sludges. Therefore the basic aim of a dewatering process is to achieve dry solids contents as high as possible. Sludge dewatering is one of the most difficult problems in waste water treatment. In the Netherlands sludge is primarily dewatered by filter presses and belt presses. In these types of dewatering equipment, a filtration and expression phase can be distinguished [1]. To get a better understanding of the sludge dewatering process, research on fundamental aspects of sewage sludge dewatering is carried out. This study is part of the larger Dutch research program entitled "Future Treatment for Municipal Waste Water, RWZI 2000". An important part of the study is the characterization of the sludge solid-water bond strength. Knowledge about the sludge solid-water bond strength as a function of the moisture content gives the possibility to predict the maximum feasible dry solids content in a certain dewatering process. The sludge solid-water bond strength can be obtained from thermal analysis techniques and from water vapour sorption isotherms.

THE PRESENCE OF WATER

Figure 1 presents schematically the way that water may be present in sludge and sludge cake. In a suspension or in a filter cake one can distinguish a water phase and a floc phase. The flocs are formed from the basic sludge particles, in many cases with the addition of flocculants. Flocculants are used to promote the aggregation of basic particles and in this way improve the release of water from sludges. Flocculants that are usually applied in waste water treatment plants are (i) $FeCl_3$ in combination with $Ca(OH)_2$ or (ii) high cationogenic polyelectrolytes.
The mechanical behaviour of flocs in a dewatering process depends on floc properties and conditions of dewatering as well. Floc properties of a given sludge depend on amount and nature of the flocculants. The flocs con-

sist of a skeleton, in which interstitial liquid is present. The properties of the basic sludge particles vary with place, season and conditions in the waste water treatment plant. Basic particles, like microbial cells, or pieces of wood, etc. contain water inside. Further hydration layers may be present at the particle surfaces.

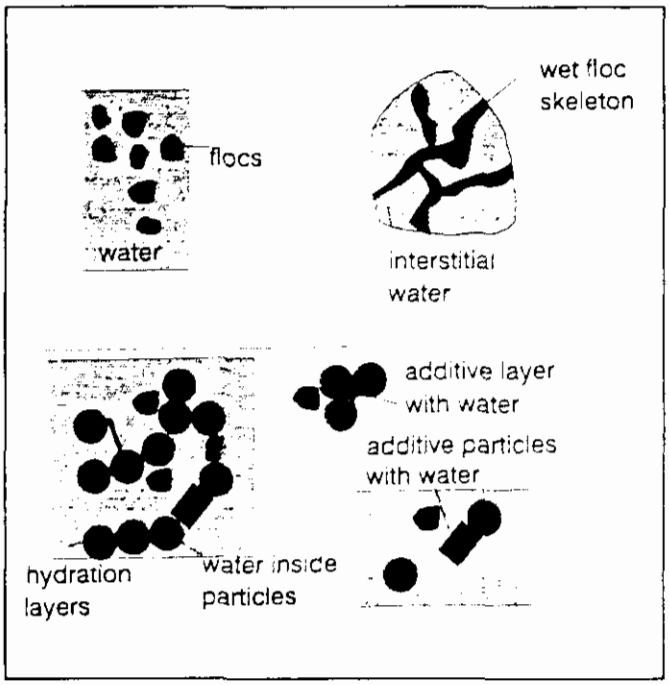


Figure 1. The presence of water in sewage sludge.

THERMAL ANALYSIS: TGA and DTA

With thermogravimetric analysis (TGA) the loss in mass of a sludge cake sample, due to vaporization of water, is measured continuously at a constant temperature. With differential thermal analysis (DTA) the heat flow required for vaporization of water out of the sludge cake sample is measured after calibration [2].
The TGA/DTA equipment gives the possibility to carry out TGA and DTA simultaneously. Knowing the sample moisture content at the beginning of the experiment, moisture content as a function of time can be determined too. The ratio between vaporization rate $\dot{m}$ (in kg/s), calculated from the TGA-experiments and heat flow to the sample q (in J/s), obtained from the DTA-experiments, is equal to the heat of vaporization of water $H_{vap,sample}$ (in J/kg) present in the sample:

$$H_{vap,sample} = \frac{q}{\dot{m}} \qquad (1)$$

The heat of vaporization of pure water is a function of temperature according to :

$$H_{vap,water} = H_{vap,water0} - (Cp_w - Cp_{wv})\,(T - 273) \qquad (2)$$

where:

$H_{vap,water0}$ = heat of vaporization of water at 273 K [2501 kJ/kg]
Cp_w = specific heat of water [4.19 kJ/kg·K]
Cp_{wv} = specific heat of water vapour [1.84 kJ/kg·K]
T = temperature [K]

The bond enthalpy H_b (in kJ/kg) is equal to the difference between measured heat of vaporization and heat of vaporization of pure water:

$$H_b = H_{vap,sample} - H_{vap,water} \qquad (3)$$

With the TGA/DTA technique the bond enthalpy can be calculated as a function of the sample moisture content.

EXPERIMENTAL

Experiments were carried out with sludge cake samples at constant temperature. Sludge cakes (diameter: 7 cm, thickness: 1 mm) obtained from a filtration cell with a pressure of 3 bar [1]. To improve the dewatering behaviour, $FeCl_3$ (10 wt% on dry solids basis) in combination with $Ca(OH)_2$ (20 wt% on dry solids basis) were added to the sludge. In all experiments, secondary sewage sludge, taken from the waste water treatment plant 'De Dommel' in the Netherlands, was used. In figure 2, a result of a TGA/DTA-experiment is given. In this experiment a sludge cake sample, having an initial mass of 32.5 mg and an initial

moisture content of 3.33 $kg_{water}/kg_{dry\ solids}$, was submitted to a constant temperature of 353 K. At the start of the experiment the vaporization rate and heat flow were relatively high. In the first drying stage, rate of vaporization remains constant and free water is transported. In this stage, the heat of vaporization in the sample is equal to the heat of vaporization of pure water. At a sample moisture content of 1.5 $kg_{water}/kg_{dry\ solids}$ vaporization rate and heat flow start to decrease and the bond enthalpy differs significantly from zero. It can be calculated that water can not be removed by filtration, when the bond enthalpy is larger than 1 kJ/kg [2]. So, from the graph given in figure 2 the conclusion can be drawn that the maximum feasible dry solids content in a filtration process of this sewage sludge is approximately 40 wt% on dry solids basis.

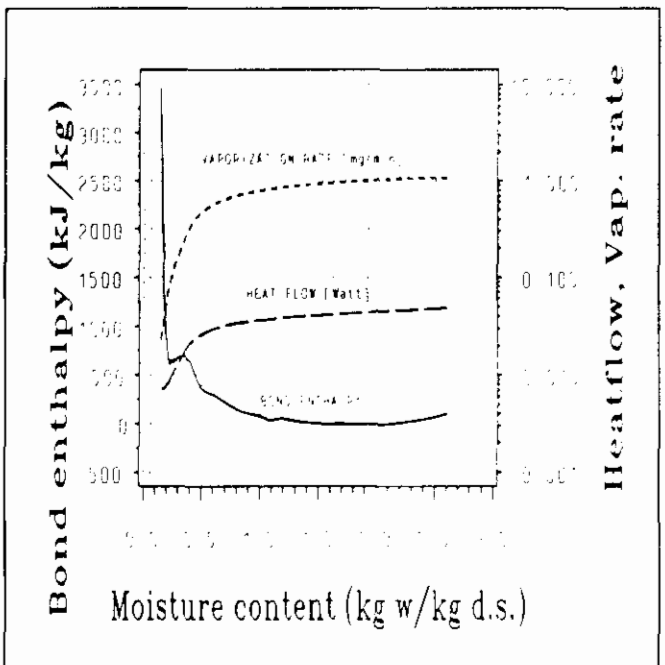


Figure 2. Measured vaporization rate, heat flow and bond enthalpy as a function of the sample moisture content.

WATER VAPOUR SORPTION ISOTHERMS [3]

Another technique to characterize the sludge-water bond is measuring water vapour sorption isotherms. A water vapour sorption isotherm of a substance is the constant temperature relation between the amount of water in the substance and its thermodynamic water activity a_w. Under normal conditions ideal behaviour of the gas phase may be assumed and the a_w equals the relative humidity of the gas phase. Thus:

$$a_w = \frac{p_w}{p_{w0}} \qquad (4)$$

With:

p_w = water vapour pressure [Pa].

p_{w0} = saturated water vapour pressure at standard temperature and pressure [Pa].

In case of bond water a_w will become significantly smaller than 1. a_w for a certain system is a function of temperature and moisture content ($0 \le a_w \le 1$).

In literature about 80 equations to describe sorption isotherms are known[4,5] because the interactions between water (sorbate) and dry substance (sorbent) are very complex. A relative simple sorption model with three parameters is the G.A.B.-model (Guggenheim[6](1966), Anderson[7](1946) and de Boer[8](1953)):

$$\frac{X_w}{X_{w1}} = \frac{C_g k a_w}{(1-k a_w)(1-k a_w + C_g k a_w)} \qquad (5)$$

with:

X_w = mass fraction of water on dry solids basis [$kg_{water}/kg_{dry\ solids}$].

X_{w1} = the amount of sorbate adsorbed when all sites contain one molecule, also named completed monolayer [$kg_{water}/kg_{dry\ solids}$].

C_g = the Guggenheim constant which depends on the nature of the interaction between sorbate and sorbent and the temperature.

k = factor which corrects the differences between the properties of watermolecules in the multilayer and the properties of pure water.

In this study the G.A.B.-equation will only be used for data reduction and won't be used for physical interpretation.
From water vapour sorption isotherms, measured at different temperatures, the differential enthalpy of wetting can be calculated by application of the Clausius-Clapeyron equation:

$$\left(\frac{\partial \ln a_w}{\partial\left(\frac{1}{T}\right)}\right)_{X_w} = \frac{H_w}{R} \qquad (6)$$

where:

H_w = differential enthalpy of wetting [kJ/kmol]
R = gas constant [8.31 kJ/kmol·K]
T = temperature [K]
a_w = water activity [-]
X_w = moisture content [$kg_{water}/kg_{dry\ solids}$]

At a given moisture content X_w the differential enthalpy of wetting can be found by plotting $\ln(a_w)$ against 1/T. The slope of the straight line is equal to H_w/R.

EXPERIMENTAL [9]

Water vapour resorption isotherms of sludge cake samples were determined with the conventional technique of vacuum exsiccators with saturated aqueous salt solutions to control the water activity. The data for the water activity of these solutions were taken from the tables of Greenspan[10] (1977). For keeping a constant temperature during equilibration the exsiccators were positioned in a thermostated water bath (± 0.1 K). Equilibrium was assumed if two subsequent weighings gave the same results.

To obtain sewage sludge cake samples, the same procedure was used as described before. From the obtained sludge cake twelve samples (mass is about 35 mg) with a diameter of 5 mm and a thickness of 1 mm were taken. The samples were dried in an oven at 383 K during 24 hours.
The twelve dry sludge cake samples were placed in twelve different exsiccators, each with their own water activity. At reaching equilibrium conditions within 24 hours, the moisture content of the samples was determined and the resorption isotherm was constructed. For three temperatures (303, 323 and 343 K) water vapour resorption isotherms were measured.
The G.A.B.-equation is fitted to the measured resorption data using the sum of least-squares method for minimizing the absolute differences between measured and calculated moisture contents X_w. This was efficiently done by using the Statistical Analysis System package (SAS).

RESULTS

Figure 3 shows the experimental data and the fitted G.A.B.-equation for three temperature levels.

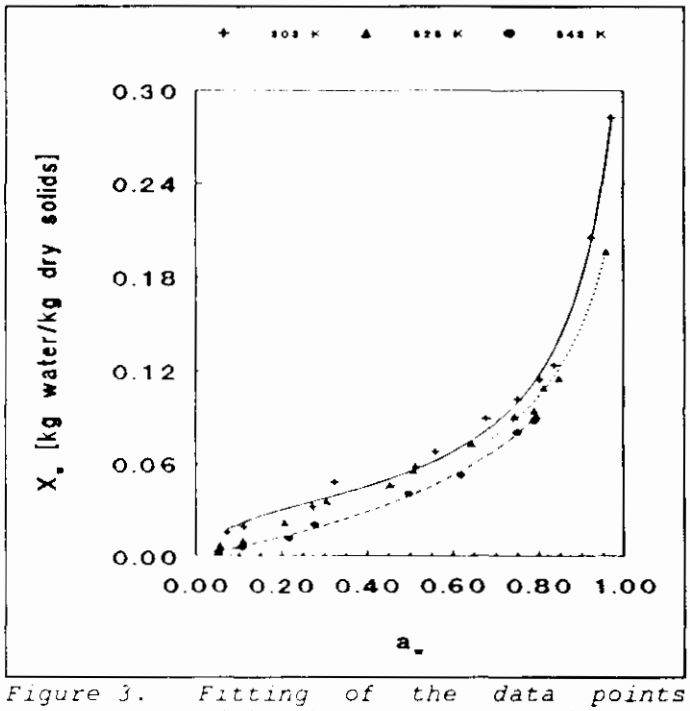


Figure 3. Fitting of the data points with the G.A.B.-equation for the water vapour resorption experiments.

For the whole a_w-range the G.A.B.-equation

describes the data points very well. In figure 4 the differential enthalpy of wetting H_w (in kJ/kg_{water}) is plotted against the moisture content X_w (in $kg_{water}/kg_{dry\ solids}$). With these data it was possible to calculate the energy to remove water per kilogram dry solids. The energy needed to reduce the moisture content of a sludge cake from 0.12 $kg_{water}/kg_{dry\ solids}$ to 0.01 $kg_{water}/kg_{dry\ solids}$ is equal to 320 $kJ/kg_{dry\ solids}$.

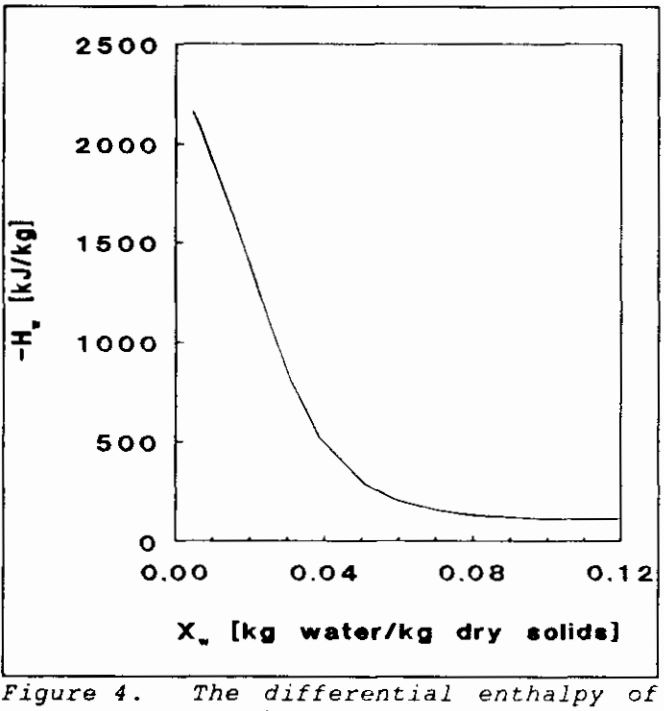


Figure 4. The differential enthalpy of wetting (H_w)

CONCLUSIONS

The TGA/DTA and water vapour sorption isotherms techniques are promising methods for characterization of the solid-water bond strength in sewage sludges. 'Bond water', which is defined as water having a bond enthalpy H_b larger than 1 kJ/kg [2], cannot be separated in a mechanical dewatering process. It appears from the TGA/DTA result that the amount of 'bond water', present in a sludge cake is equal to 60 wt% on water base. In this preliminary result it is not possible to compare the TGA/DTA and water vapour sorption isotherms results. This is due to the different pretreatment procedures. The water vapour sorption isotherm technique will be improved by measuring water vapour desorption isotherms of sewage sludge instead of resorption isotherms.

The water vapour sorption isotherms can be described very well with the G.A.B.-equation.

ACKNOWLEDGEMENT

This work is financially supported by the "Institute of Inland Water Management and Waste Water Treatment (RIZA)" and the "Foundation for Applied Waste Water Research (STORA)" in the Netherlands.

NOTATION

a_w	=	water activity	[-]
C_g	=	Guggenheim parameter	[-]
C_{pw}	=	specific heat of water	[J/kg·K]
C_{pwv}	=	specific heat of water vapour	[J/kg·K]
H_b	=	bond enthalpy	[kJ/kg]
$H_{vap,sample}$	=	heat of vaporization of water present in sample	[kJ/kg]
$H_{vap,water}$	=	heat of vaporization of water	[kJ/kg]
H_w	=	differential enthalpy of wetting	[kJ/kmol]
k	=	correction factor	[-]
$\dot{m}$	=	vaporization rate	[kg/s]
p_w	=	vapour pressure	[Pa]
p_{w0}	=	saturated vapour pressure	[Pa]
q	=	heat transfer rate or heatflow	[J/s]
R	=	gas constant	[J/mol·K]
T	=	temperature	[K]
X_w	=	moisture content	$[kg_{water}/kg_{dry\ solids}]$
X_{w1}	=	monolayer value	$[kg_{water}/kg_{dry\ solids}]$

LITERATURE CITED

1. La Heij, E.J., Herwijn, A.J.M., Coumans, W.J. and P.J.A.M. Kerkhof, "Filtration and Expression of Sewage Sludge,"presented at the 1992 Annual Meeting,AIChE, Miami Beach (November 1992).

2. Dohmen, P.C.J., "Investigation of the Sludge Solid-Water Bond Strength with Thermal Analysis Techniques," Ir. Thesis Eindhoven University of Technology, The Netherlands (1992).

3. v.d. Berg, C., "Vapour Sorption Equilibria and Other Water-Starch Interactions; a Physico-Chemical Approach," Ph.D.Thesis Wageningen University of Agriculture, the Netherlands (1981).

4. Iglesias, H.A.and J. Chirife, *Handbook of Food Isotherms, Watersorption Parameters for Food Components*, Academic Press Inc., New York (1982).

5. v.d. Berg, C. and S. Bruin, "Wateractivity and its Estimation in Food Systems: Theoretical Aspects," paper presented at: Second International Symposium on Properties of Water in Relation to Food Quality and Stability (ISOPOW-II), Osaka, Japan (September 1978).

6. Guggenheim, E.A., *Applications of Statistical Mechanics*, Clarendon Press, Oxford (1966).

7. Anderson, R.B., *J.Am.Chem.Soc.*, **68**, 686 (1964).

8. de Boer, J.H., *The Dynamical Character of Adsorption*, 2nd ed., Clarendon Press, Oxford (1968).

9. van Dijke, D.Q.A., "Design and Development of Equipment for Measuring Water Vapour Sorption Isotherms," Ir. Thesis Eindhoven University of Technology, Eindhoven (1992).

10. Greenspan, L., "Humidity Fixed Points of Binary Saturated Aqueous Solutions," in *J. Res. Nat.Bur.Standards*, **81A**, 89 (1977).

FUNDAMENTAL ASPECTS OF SLUDGE FILTRATION AND EXPRESSION

Erik J. La Heij and Piet J.A.M. Kerkhof

(Laboratory for Separation Technology, Dept. of Chemical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, the Netherlands)

SUMMARY

The filtration and expression behaviour of sewage sludge is discussed. Due to the increase of costs for controlled dumping and transport and more severe environmental legislation the need for decreased sludge volumes is rising. Filtration and expression are the cheapest dewatering operations and it is therefore desirable to remove the maximal feasible amount of water by mechanical dewatering. High dry solids contents of 35-40 wt% can already be reached at pressure of 300-400 kPa and optimal flocculation conditions; however at pressures of 6-10 MPa dry solids contents of 60 wt% can be reached. Further the modelling of the dewatering is discussed; model and experiment show acceptable agreement.

1. INTRODUCTION

In the Netherlands sludge production from municipal waste water treatment plants is still increasing; on dry solids base the 1988 production was 282,000 tons and a conservative estimate for the year 2000 is 400,000 tons/yr. As is illustrated in Fig.1, after 1985 the use in agriculture and compost/soil production has been decreasing, and virtually all the rest has been disposed of by controlled dumping. Incineration still only accounts for a few % of sludge disposal. In the future the use in agriculture will decrease due to the increase of more severe limits of allowed heavy metal concentration; an overview is given in Fig.2. Costs of controlled dumping as well as those of transport are rising and environmental regulations tend to decrease the number of available sites. It is therefore to be expected that incineration and possibly other processes, like wet oxidation, will increasingly be needed in the future to dispose of the waste sludge. A decrease of the sludge water content is of the utmost importance in all cases to decrease transport costs. For controlled dumping it is necessary to decrease needed site volume. For incineration it is needed to operate under autothermal combustion conditions to decrease energy costs and decrease capital and operating costs by reduction of the flue gas stream from the incinerator. As stated by van Starkenburg and Rijs [2] in their view of needs for future research : *"The processing of sewage sludge to yield a useful product is in fact an option of the past. The main objective of the methods of sludge processing therefore is reduction of the problem by reducing the volume".*

Fig. 1. Production and disposal of sludge in the Netherlands (after data of Werumeus Buning [1])

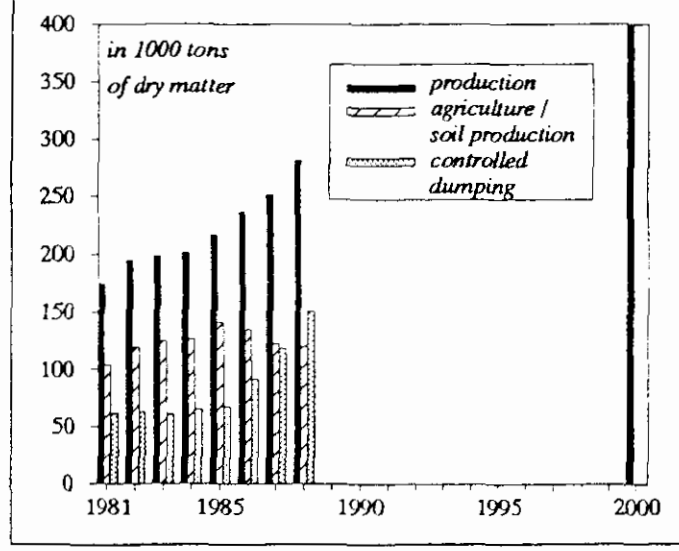
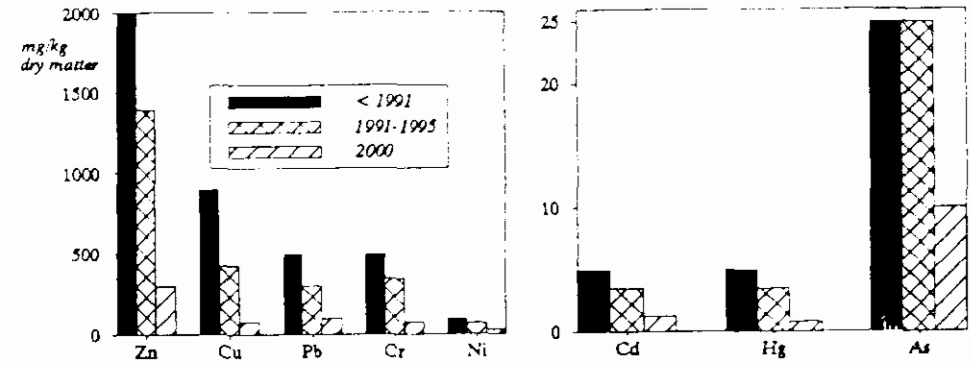
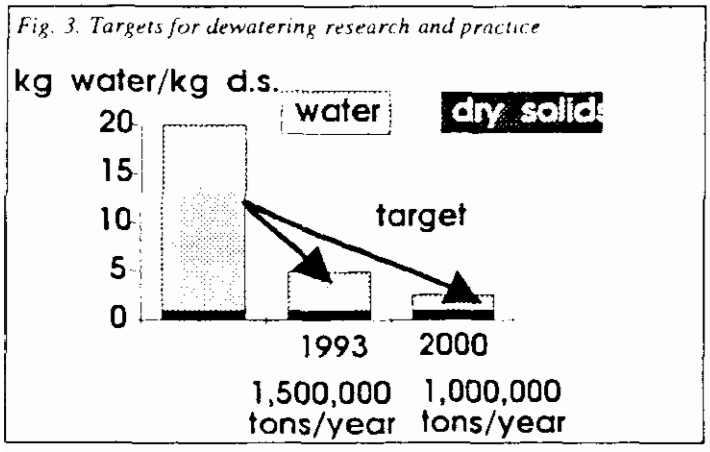


Fig. 2. Limits on heavy metal concentration for the agricultural use of sewage sludge (based on data of Werumeus Buning, [1])



The dry solids content of sludge before dewatering treatment is typically 2-4 wt%, while after mechanical dewatering in practice dry solids contents of 17-25 wt% are typical. In some cases ds-contents of 30 wt% have been found. The targets for dewatering research may thus be presented as in Fig.3. Taking the present average water content after dewatering at 4 kg water/kg ds, we must aim at a reduction in future to 1.5 kg water/kg ds, corresponding to 40 wt% solids. This would mean that in spite of an expected growth of sludge from 300,000 tons dry solids/yr. now to 400,000 tons dry solids/yr. in 2000, we would still have a considerable reduction of 500.000 tons/yr. on a total base. This would correspond to a yearly savings of about Dfl. 33,000,000., calculated at present cost of Dfl. 660,-/ton for incineration (Werumeus Buning, [1]). However the savings for our society may be much higher : capital and energy costs per ton decrease. If moreover only polymeric flocculants will be used and no more $FeCl_3$ / $Ca(OH)_2$ a considerable reduction in tonnage dry solids will also result. Thus very roughly a potential savings of Dfl 80,000,000/yr. could be seen as a reasonable target.

Fig. 3. Targets for dewatering research and practice



As stated by the previous cited authors, van Starkenburg and Rijs [2], about dewatering research : "*What generally happens during the processing of sludge is still largely unknown. Research in this field should proceed without delay*". In the following we will report on progress made in understanding and quantification of the phenomena crucial to the dewatering by means of filtration and expression, following from the study done at our laboratory by the Sludge Dewatering Projectteam : ir. Arend J.M. Herwijn, drs. Erik J. La Heij, and ing. Paul M.H. Janssen, in co-operation with dr.ir. W. Jan Coumans and prof.dr.ir. Piet J.A.M. Kerkhof. Also a considerable contribution has been made by our undergraduate students of which 10 have done their Ir-thesis on this subject; a very valuable contribution was made by ir. Gerben D. Mooiweer in guiding statistical interpretation of results. The project takes up about 15 % of the larger Dutch national project : "Municipal Waste Water Treatment 2000 (RWZI-2000)". Roughly we have divided

the field into two themes : sludge characterization and dewatering fundamentals. On the former dr. Coumans reports during this workshop [3].

At the first workshop in Heelsum we have indicated some of the phenomena we had at that time been studying for somewhat more than a year [4] and indicated some possible directions for modelling filtration and expression. In the following we will treat some of our progress in this area and will discuss the relevance for practical operation.

2. LABORATORY EXPERIMENTS

In order to study the filtration and expression behaviour we have made several laboratory set-ups which we will describe in short in the following paragraphs.

2.1. The Filtration-Expression Cell (FE-cell)

The cell, as shown in Fig.4, consists of a perspex cylinder with a porous bottom-plate. Before filtration a filter paper is placed on the porous plate and the flocculated sludge is introduced into the cell. After that gas pressure is applied to the space above the sludge and filtration starts. The filtrate is collected in a beaker on a balance and data are transferred to an on-line computer. After filtration has been completed a non-porous piston is placed on the sludge cake and gas pressure is applied above the piston. Thus the filter cake is expressed and the expression rate is again followed by means of the liquid flowing to the balance. In some experiments first a gravity filtration is carried out, after which an additional amount of water is added, which is pressed through the fixed sludge amount under pressure.

Fig.4. Diagram of the Filtration-Expression Cell

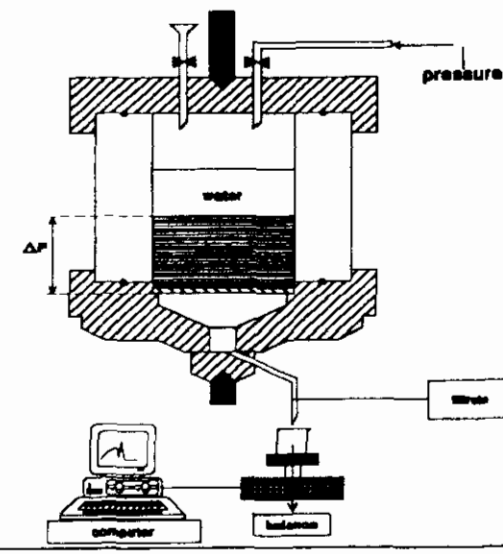
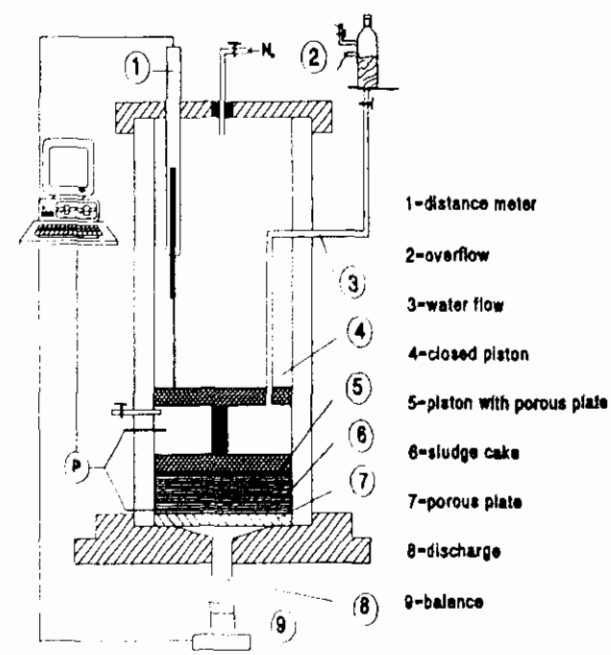


Fig.5. Diagram of the Compression-Permeability Cell



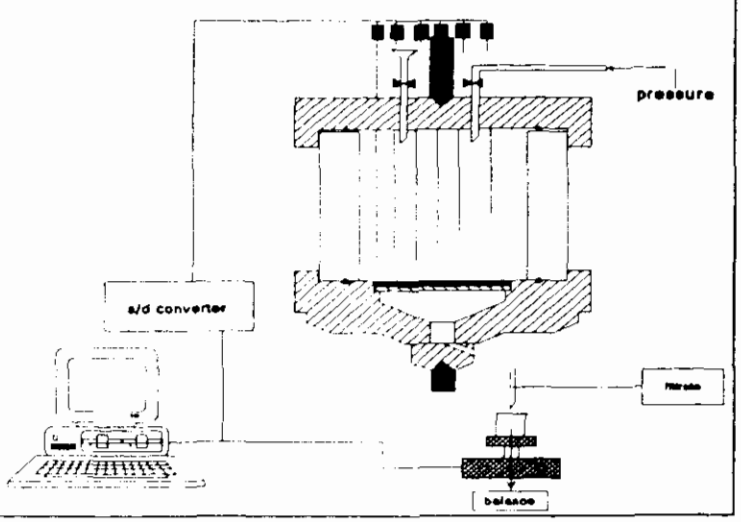
2.2. The Compression-Permeability Cell (CP-cell)

In modelling the dynamic flow of filtrate during filtration and expression the relations between permeability, porosity, and compressive pressure are of great importance. The CP-cell with which these relations are determined is shown in Fig.5. It consists again of a perspex cylinder with a porous metal bottom plate, on which a filter paper is placed. Flocculated sludge is introduced and a double piston system is lowered upon the sludge. The lower piston is porous, and the space between the pistons is filled with water. By applying gas pressure on the upper, solid piston, a compressive force is exerted on the sludge mass. Through a tube a small flow of water is allowed to flow through the lower piston, the sludge cake and the filter medium. By registration of the flow rate and of the liquid pressure difference the permeability can be measured. By means of a displacement transducer the cake thickness is known, from which the porosity can be deduced.

2.3. Pressure Distribution Cell

This cell is constructed in the same fashion as the filtration cell, but it has been equipped with a number of capillaries of different length, which are connected to pressure transducers. With these tubes it is possible to measure the liquid pressure at different heights inside the filter cake. By using a mixture of clay and glycerol as a piston a sludge filter cake can be expressed.

Fig.6. The Pressure Distribution Cell

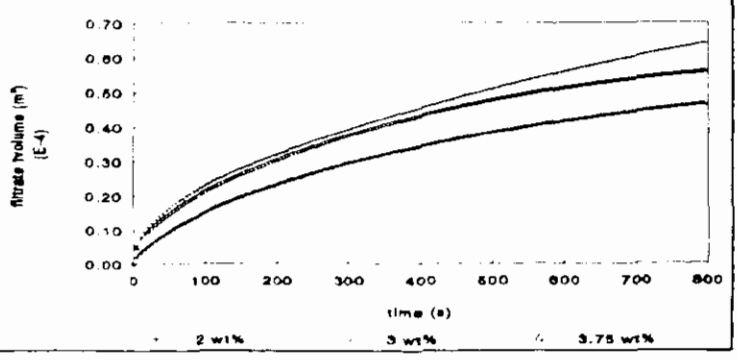


3. EXPERIMENTAL RESULTS

3.1. Filtration and expression experiments

Typical experimental results of a filtration experiment are shown in Fig.7, in which Eindhoven sludge, flocculated with 10 wt% $FeCl_3$ on dry solids basis was filtered at 0.5 bar pressure difference in the filtration cell at different initial solids contents of the sludge. A first interpretation of such filtration curves is to determine the effective specific cake resistance α, as defined by :

Fig.7. Typical filtration curves for sludge at different initial solids content in slurry



$$\alpha = R_c / w$$

$$R_c = \frac{\Delta p_l}{\mu u_l} = L_c / K \qquad (1)$$

in which R_C is the cake resistance, w is the cake mass per unit area, Δp_l is the filtration pressure, μ is the liquid viscosity, u_l is the superficial liquid velocity, L_C is the cake thickness and K is the permeability.

The specific cake resistance is a good measure of sludge characteristics and will depend on the type of sludge, the flocculation treatment and on the filtration pressure. A typical example is shown in Fig.8, in which α is plotted vs. the dosage of $FeCl_3$. In this case a minimum is observed, indicating an optimal dosage of

Fig. 8. Effect of flocculant dosage on specific cake resistance α for Mierlo sludge flocculated with $FeCl_3/Ca(OH)_2$, at Δp = 0.5 bar

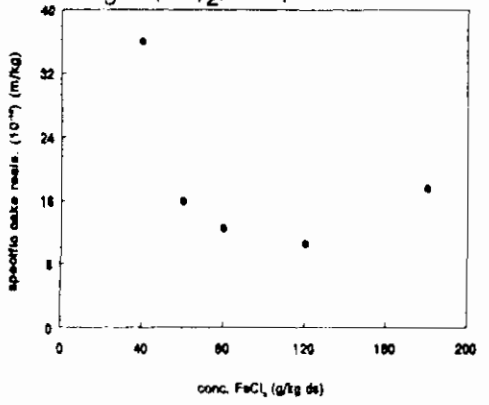
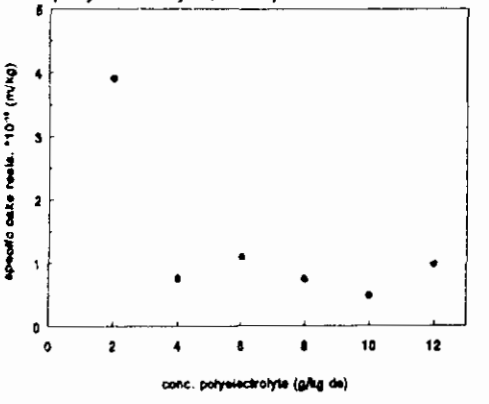


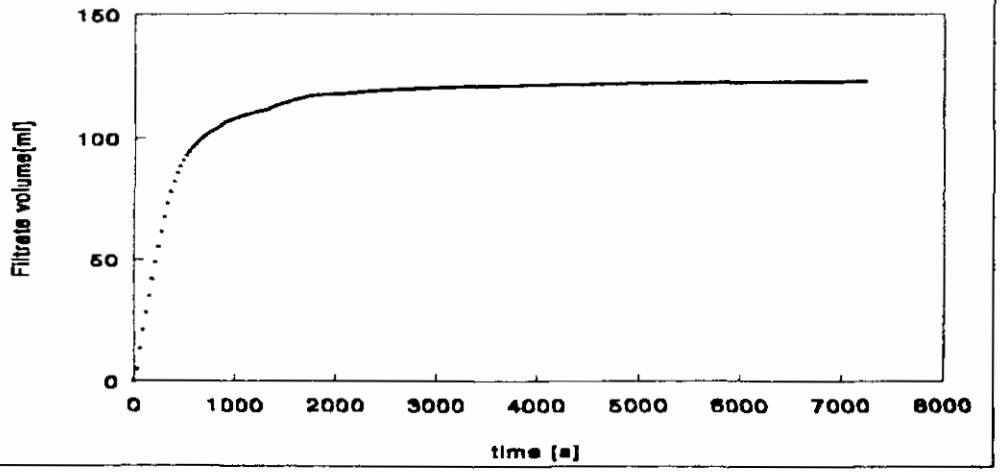
Fig. 9. Effect of flocculant dosage on specific cake resistance α for Mierlo sludge flocculated with polyelectrolyte, at Δp = 0.5 bar



flocculant around 100 g/kg dry sludge. With other sludges the increase at overdosage is not as clear as in this picture, but is always of the order of 10 % or higher. Analogous results have been obtained with addition of polyelectrolytes, which is illustrated in Fig. 9.

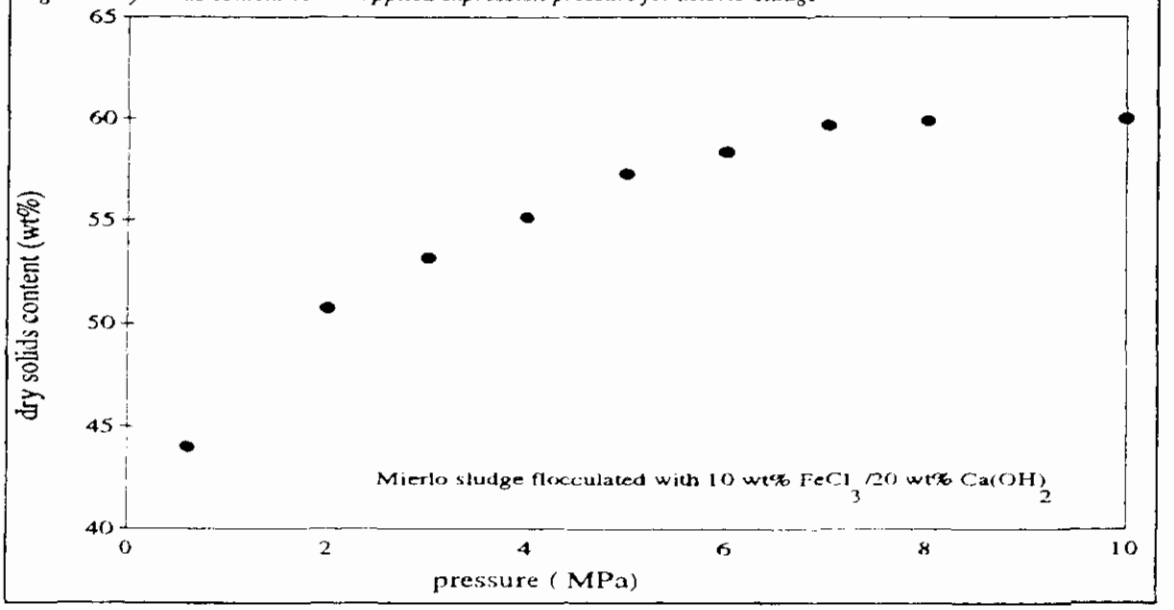
In Fig. 10 the expression curve of a filter cake is shown. Characteristic is the rapid initial expression, followed by a slow consolidation.

Fig.10. Expression of a sludge filter cake



In Fig. 11 results of high pressure expression are shown. It can be seen that dry solids contents of 60 wt% can be reached at pressures of 10 MPa. The values shown in Fig. 11 include flocculant dosage.

Fig. 11. Dry solids content versus applied expression pressure for Mierlo sludge



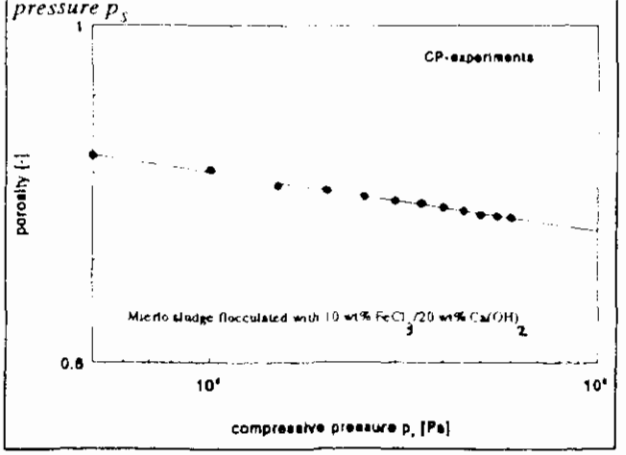
3.2. Permeability and porosity in relation to compressive pressure

In Fig. 12 and 13 results of typical compression-permeability experiments are shown. Relations between porosity ε, permeability K and compressive pressure p_s are found. In most cases these relations can be fitted with a power law function (van Veldhuizen [6]). Relations which can be used are (Tiller et al. [7]):

$$\varepsilon = \varepsilon_0 \left(1 + \frac{p_s}{p_a} \right)^{-\lambda}$$

$$K = K_0 \left(1 + \frac{p_s}{p_a} \right)^{-\delta} \qquad (2)$$

Fig. 12. CP-experiment. Porosity ε versus compressive pressure p_s



where ε_0 and K_0 are the porosity and the permeability at zero compressive pressure respectively; λ and δ are compressibility coefficients and p_a is an arbitrary constant. Compression-permeability experiments are also very useful for characterisation of different sludges. It quickly gives an idea of the compressibility of the sludges and therefore about the dry solids contents at different applied expression pressures.

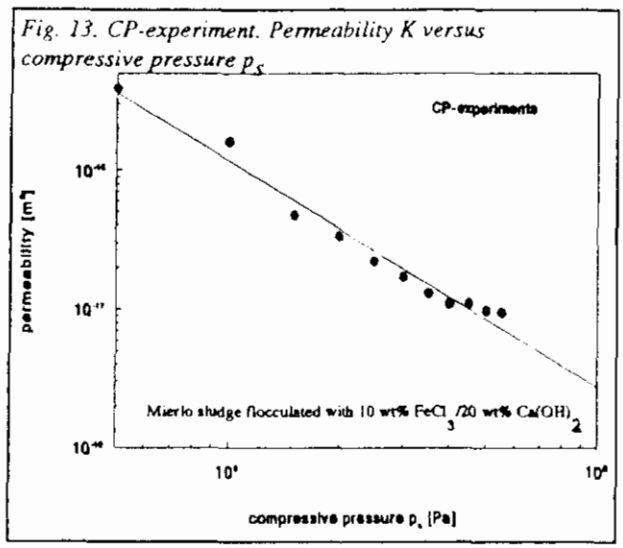
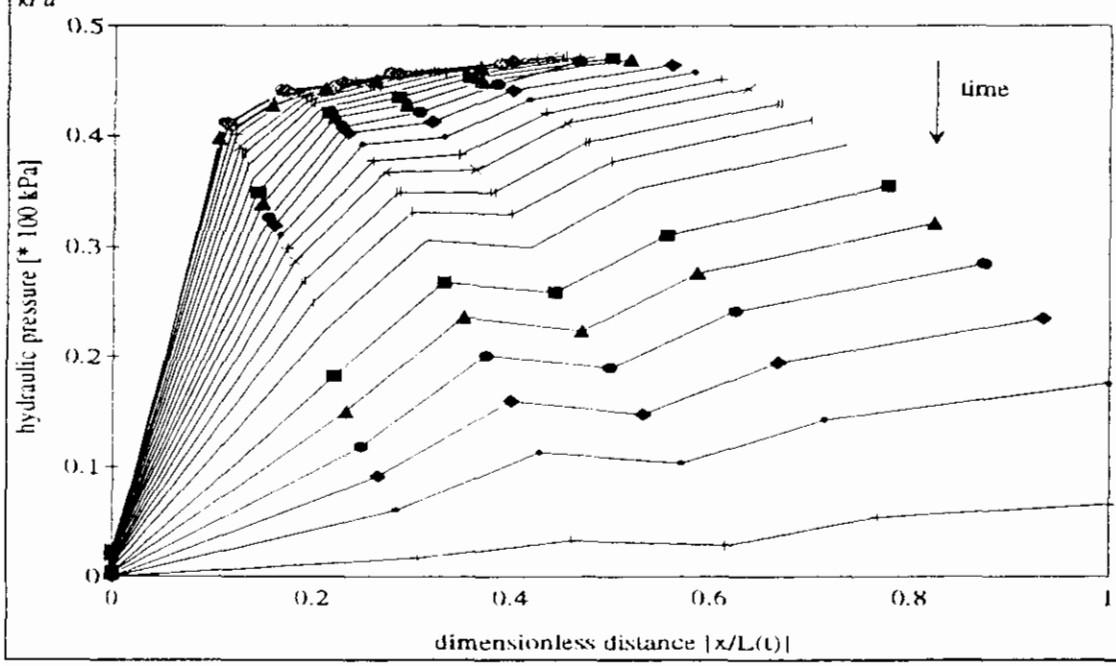


Fig. 13. CP-experiment. Permeability K versus compressive pressure p_s

3.3 Pressure distributions in sludge filter cakes

In Fig. 14 the hydraulic pressure distribution during the expression phase of an Eindhoven sludge filter cake flocculated with $FeCl_3$ and $Ca(OH)_2$ is shown.
The first profile in Fig. 14 is more or less (exact transition point is very difficult to determine) the end of the filtration phase, showing hardly any gradient throughout the cake. Only near the filter medium (x/L(t)=0) a steep gradient appears, indicating only compression near the filter medium. This means that the dry solids content after filtration is still very low. At the end of the expression phase the hydraulic pressure throughout the cake almost equals zero, indicating a uniform cake structure.

Fig. 14. Hydraulic pressure distribution during the expression phase in a filter cake. Sludge from rwzi Eindhoven flocculated with 10 wt% $FeCl_3$ and 20 wt% $Ca(OH)_2$ on dry solids base. Expression pressure 48 kPa



4. MODELLING THE FILTRATION- AND EXPRESSION BEHAVIOUR.

4.1 Governing equations

To model the filtration- and expression behaviour of sewage sludge attention must be focused on flow through compressible cakes. Therefore flow rate equations, stress balances, constitutive equations and continuity equations are needed. For

the flow rate equation the Darcy-Shirato equation (Shirato et al. [6]) is used which takes into account the solids movement:

$$v_l - v_s = \frac{1}{\varepsilon}\frac{K}{\mu}\frac{\partial p_l}{\partial x} \tag{3}$$

where v_l and v_S are the linear liquid and solids velocity respectively. A simplified force balance leads to the following equation:

$$\frac{\partial p_l}{\partial x} + \frac{\partial p_s}{\partial x} + \left(\rho_l \varepsilon + \rho_s (1-\varepsilon)\right) g = 0 \tag{4}$$

The continuity equation reads:

$$\left(\frac{\partial \varepsilon}{\partial t}\right)_x = \left(\frac{\partial u_l}{\partial x}\right)_t \tag{5}$$

Combination of the above equations leads to a partial differential equation, which describes the change of the porosity in time and place in a filter cake:

$$\left(\frac{\partial \varepsilon}{\partial t}\right)_x = u_{lm}\left(\frac{\partial \varepsilon}{\partial x}\right)_t + \frac{\partial}{\partial x}\left[\frac{K}{\eta}(1-\varepsilon)\left((\rho_s - \rho_l)(1-\varepsilon)g + \left(\frac{\partial p_s}{\partial x}\right)_t\right)\right] \tag{6}$$

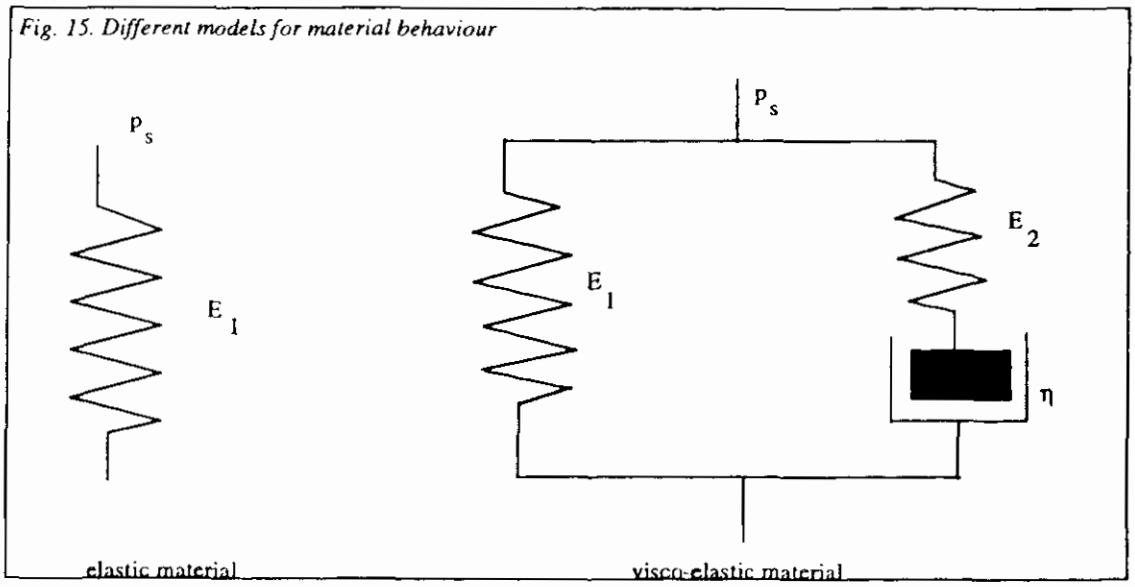
where u_{lm} is the superficial liquid velocity through the filter medium, ρ_S the density of the solids, ρ_l the density of the liquid and g the gravity acceleration. Depending on the boundary conditions the filtration- or the expression phase can be modelled (La Heij et al. [8]). However, before the partial differential equation with the right boundary conditions can be solved, a constitutive equation must be chosen.

4.2 Constitutive equations

Constitutive equations describe the deformation behaviour of the solids in a filter cake and can only be determined experimentally. The CP-cell (discussed in section 2.2 and 3.2) is an apparatus to determine these constitutive equations; relations between permeability K, porosity ε and compressive pressure p_S. Using the relations found with the CP-cell for modelling, the material is assumed to behave non-linear elastic. This means that at a given compressive pressure the filter cake deforms instantaneously apart from the hydrodynamic resistance. This non-linear elastic material behaviour can be regarded as a spring with a variable elastic modulus E_1, see Fig. 15. The elastic modulus increases with decreasing porosity.
If it takes some time before the material deforms when a certain compressive pressure is placed on the solids, the material behaves visco-elastic. Different spring-dash pot models can be used to describe the material behaviour. In Fig. 15 a three parameter model is shown. The differential equation describing the strain ϵ as a function of time can be written as:

$$\left(\frac{\partial \epsilon}{\partial t}\right) = -\frac{p_s + E_1 \epsilon + \tau \frac{\partial p_s}{\delta t}}{\left(\tau(E_1 + E_2) + \tau \epsilon \frac{\partial E_1}{\partial \epsilon}\right)} \tag{7}$$

Fig. 15. Different models for material behaviour



where τ ($=E_2/\eta$) is the relaxation time. The strain ϵ is related to the porosity ε as follows:

$$\epsilon = \frac{(1-\varepsilon_0)}{(1-\varepsilon)} - 1 \qquad (8)$$

The relaxation time τ determines the rate of deformation of the material. In equilibrium situation all the pressure rests on spring E_1 and therefore the same value for pure elastic material for E_1 can be used. Because the material deformation and the liquid flow through the cake occur simultaneously, the relaxation time τ can only be determined directly from a filtration- or expression experiment.
Equations (6) and (7) must be solved simultaneously to calculate locally and at every time the change of the porosity in the filter cake.

4.3 Modelling results

Because the porosity can be calculated as a function of time and place, the compressive pressure and therefore also the hydraulic pressure can be calculated. In Fig. 16 calculated hydraulic pressure profiles for the expression phase based on non-linear elastic material behaviour are shown. Compared to the measured profiles, shown in Fig. 14, there is a good agreement between model and experiment. In Fig. 17a the average dry solids content versus the time for different expression pressures are shown, in Fig. 17b the model calculations are shown. The sludge was flocculated at optimal conditions. Again there is an acceptable agreement between experiment and model.
According to the model calculations the equilibrium situation is reached somewhat faster than in the experiment. This is caused by the fact that for the model calculations elastic material behaviour is assumed. Further it can be seen from Fig. 17 a and b that the final equilibrium situation is reached at the same time regardless of the applied expression pressure. Finally it can be seen from Fig. 17b that already at 400 kPa dry solids contents of about 38 wt% can be reached. In Fig. 18 a and b

experiments and model calculations for the expression of sludge flocculated with polyelectrolyte are shown. Because the material deforms quite slowly, visco-elastic material behaviour must be assumed. From Fig. 18b it can be seen that there is a good agreement between model and experiment. In Fig. 19 the expression time versus cake thickness according to experiment and model is shown. Again there is an acceptable agreement between model en experiment. The dewatering time increases with the square of the cake thickness.

Fig. 16. Calculated hydraulic pressure profiles for the expression phase for sludge from rwzi Eindhoven flocculated with 10 wt% $FeCl_3$ and 20 wt% $Ca(OH)_2$ on dry solids base. Expression pressure 48 kPa

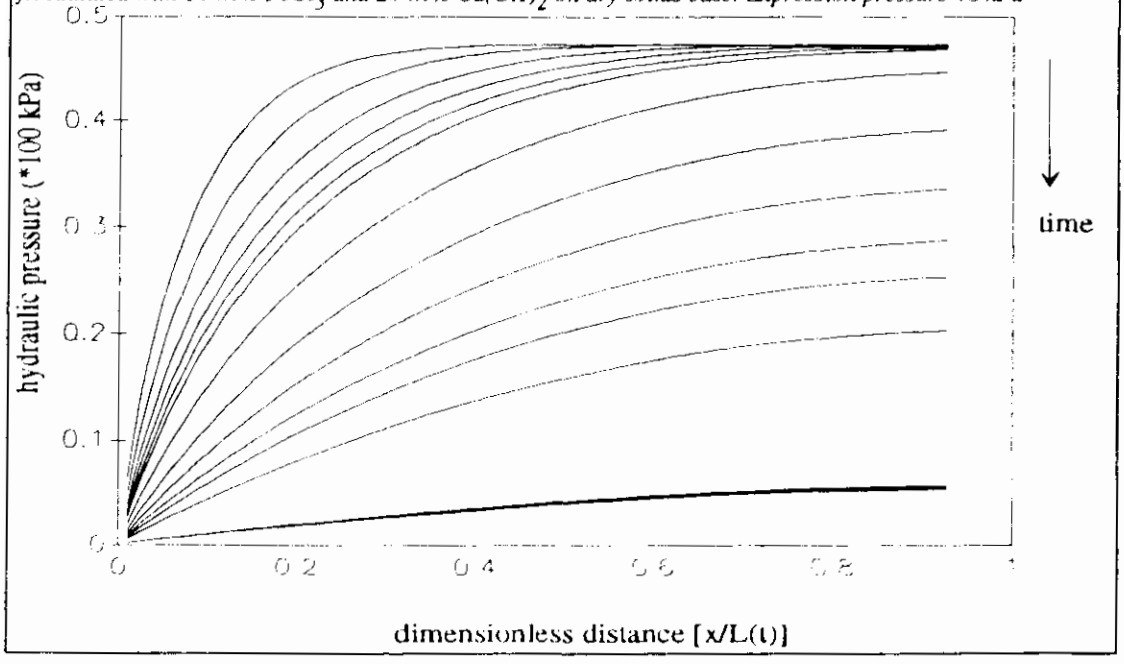


Fig. 17a. Average dry solids content versus expression time; experiment. Mierlo sludge flocculated with 15 wt% $FeCl_3$ and 20 wt% $Ca(OH)_2$ on dry solids base

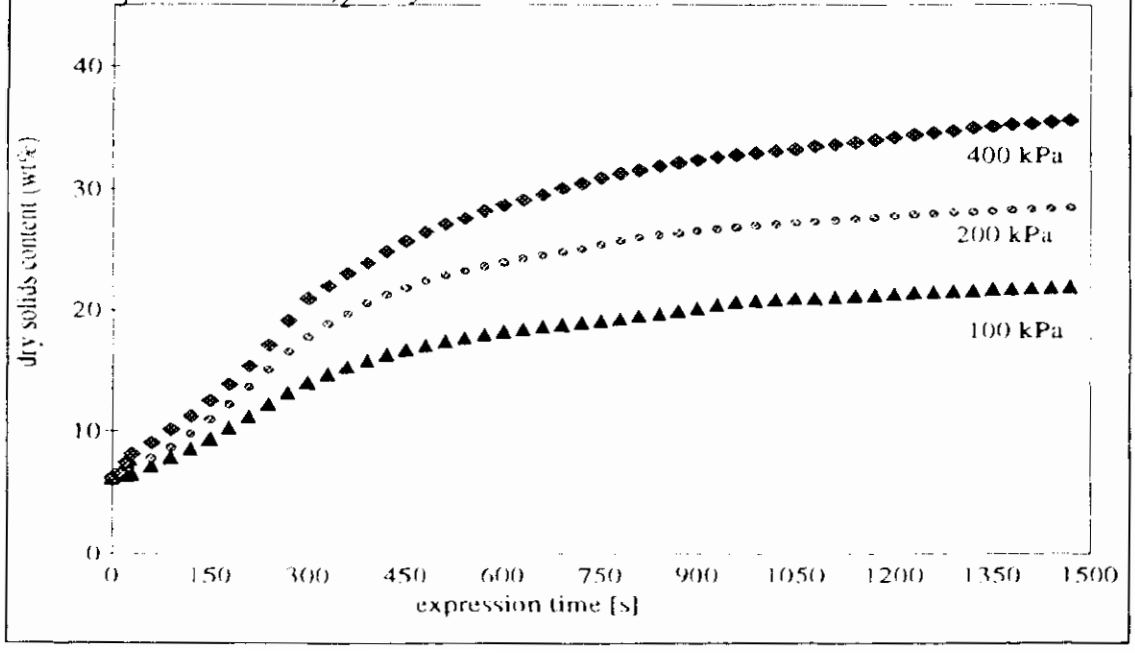


Fig. 17b. Average dry solids content versus expression time; model. Mierlo sludge flocculated with 15 wt% $FeCl_3$ and 20 wt% $Ca(OH)_2$ on dry solids base

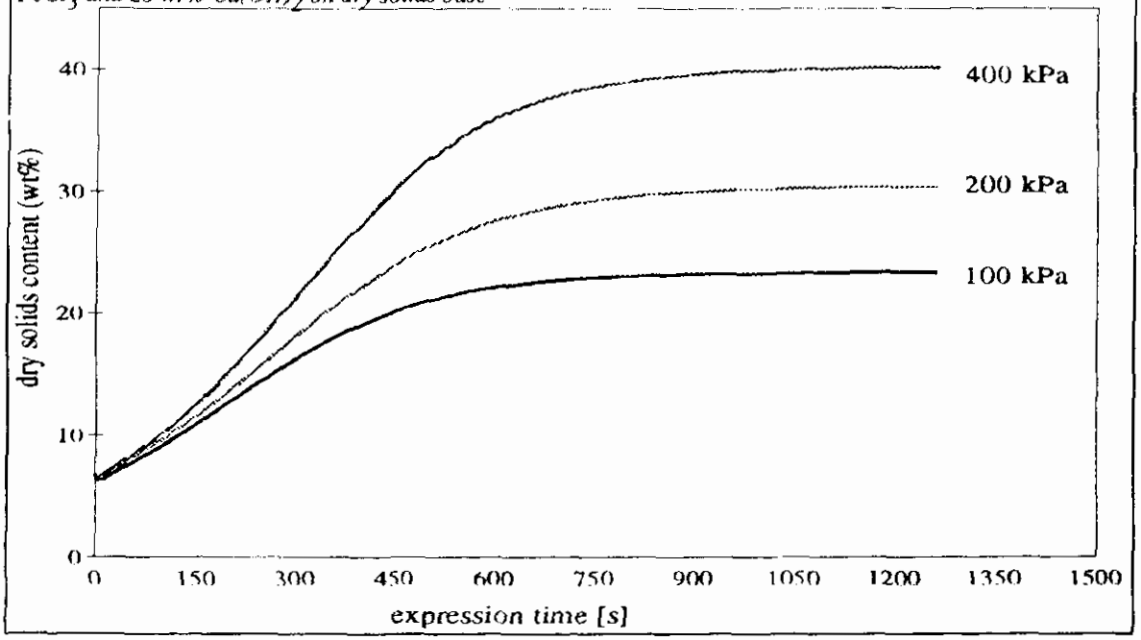


Fig. 18a. Average dry solids content versus expression time; experiment and model (elastic and visco-elastic behaviour) Mierlo sludge flocculated with 1.5 wt% polyelectrolyte

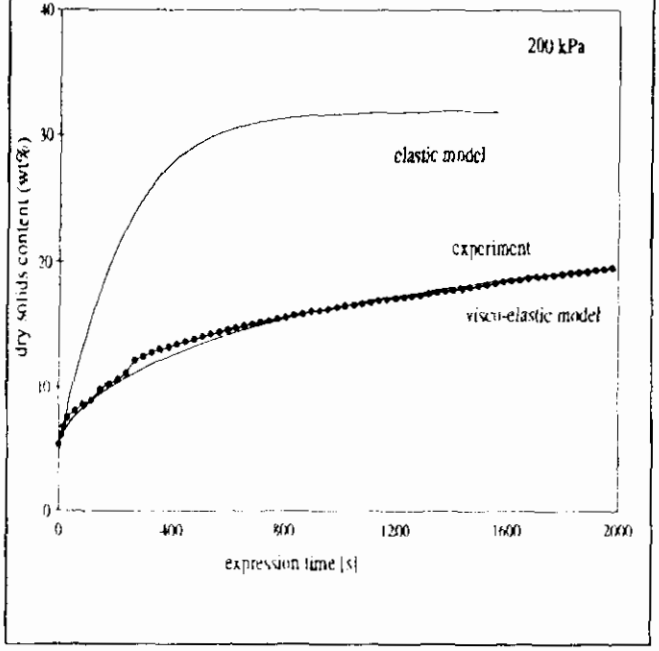


Fig. 18b. Average dry solids content versus expression time; experiment and model (elastic and visco-elastic behaviour) Mierlo sludge flocculated with 1.5 wt% polyelectrolyte

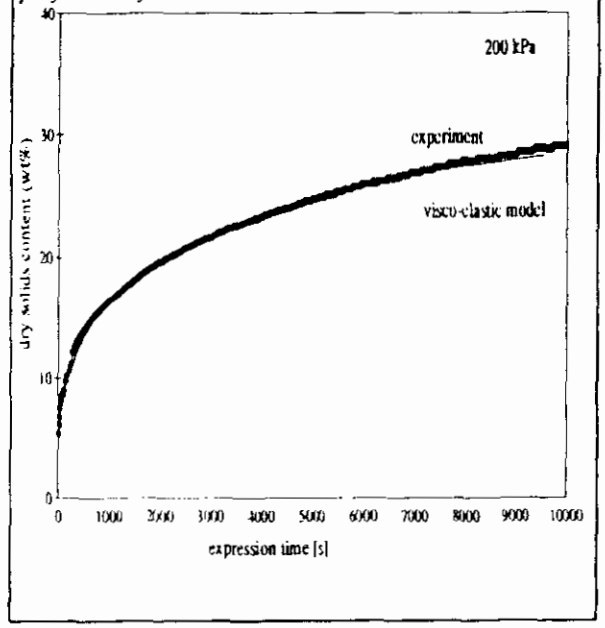
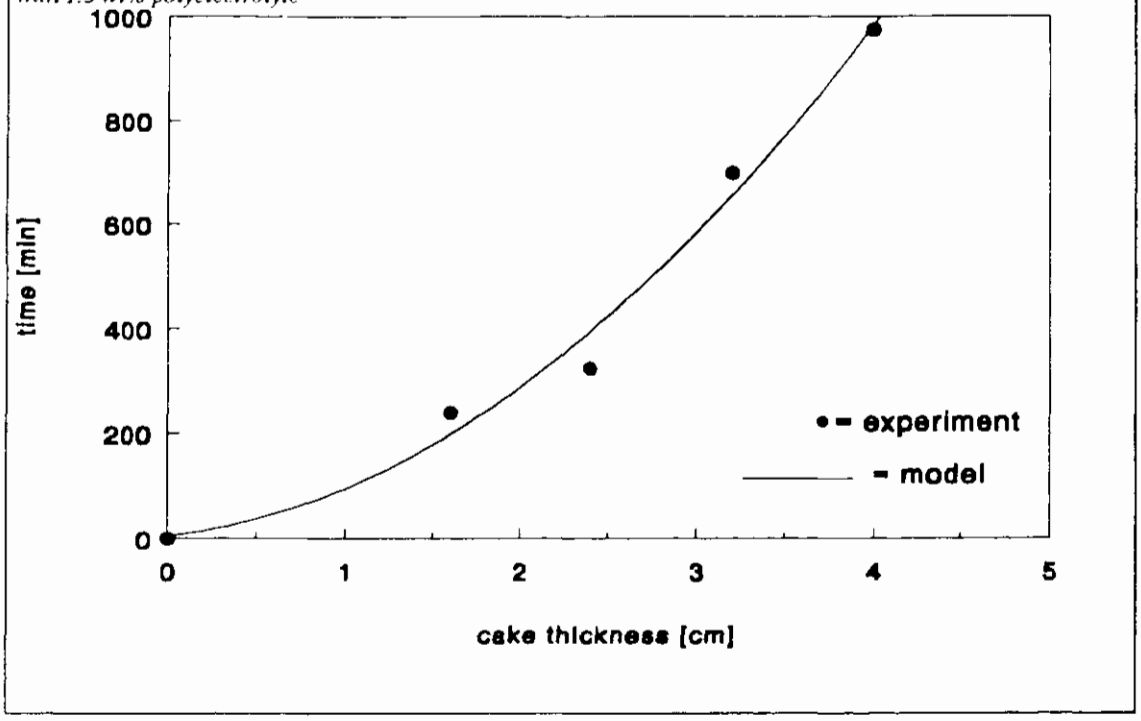


Fig. 19. Expression time versus cake thickness according to experiment and model. Mierlo sludge flocculated with 1.5 wt% polyelectrolyte



5. CONCLUSIONS

With the above discussed models the dewatering behaviour of sewage sludges can be predicted well. The material behaviour can be either non-linear elastic or non-linear visco-elastic. These fundamental models can be considered to form a good base for actual equipment and operating models, with which optimization of design and operation can be carried out.

Quickest dewatering always occurs at an optimum flocculant dosage (inorganic as well as organic flocculant). Characteristic for the expression of sewage sludges is the rapid initial expression followed by a slow consolidation. The time at which the equilibrium situation is reached, is independent of the filtration/expression pressure. At these equilibrium situations already at low pressures (300-400 kPa) high dry solids contents (35-40 wt%) can be reached. However at pressure of 6-10 MPa dry solids contents of 60 wt% can be reached. Further the dewatering times increase with the square of the cake thickness.

List of symbols

ϵ	strain	-
E_1	elastic modulus	Pa
E_2	elastic modulus	Pa
g	gravity acceleration	$m\ s^{-2}$
K	permeability	m^2
K_o	permeability at top of filter cake (p_s=0)	m^2
L_c	cake thickness	m
p	applied filtration/expression pressure	Pa
p_a	constant in equation 2	Pa
p_l	hydraulic pressure	Pa
p_s	*compressive pressure*	Pa
R_c	cake resistance	m^{-1}
t	time	s
v_l	linear liquid velocity	$m\ s^{-1}$
v_s	*linear solids velocity*	$m\ s^{-1}$
w	cake mass per unit area	$kg\ m^{-2}$
u_{lm}	superficial liquid velocity through filter medium	$m\ s^{-1}$
u_l	superficial liquid velocity	$m\ s^{-1}$
x	distance in filter cake	m

Greek symbols

α	specific cake resistance	$m\ kg^{-1}$
ε	porosity	-
ε_o	porosity at top of filter cake (p_s=0)	-
η	viscosity dash pot	Pa s
μ	viscosity filtrate	Pa s
ρ_l	density liquid	$kg\ m^{-3}$
ρ_s	density solids	$kg\ m^{-3}$
τ	relaxation time	s

Literature cited

[1] Werumeus Buning W.G.
New techniques of sludge management in the Netherlands
First Dutch-Japanese workshop on the treatment of municipal waste water, 8-11 April 1991, Heelsum, the Netherlands, part I, nr. 9.

[2] van Starkenburg W., Rijs, G.B.J.
Needs for research in the future
First Dutch-Japanese workshop on the treatment of municipal waste water, 8-11 April 1991, Heelsum, the Netherlands, part II, nr. 25.

[3] Herwijn, A.J.M., Coumans, W.J.
Characterisation of sewage sludges, fundamentals and results
Workshop sewage sludge the Netherlands-Japan, 17-23 October,1993, Miyazaki, Japan

[4] Kerkhof, P.J.A.M.
Some fundamental aspects of sludge dewatering

First Dutch-Japanese workshop on the treatment of municipal waste water, 8-11 April 1991, Heelsum, the Netherlands, part I, nr. 7.

[5] Veldhuizen, A.J.W. van
Compression behaviour of sewage sludge
ir-thesis, October 1991 (in Dutch)

[6] Shirato, M., Sambuichi, M., Kato, H., Aragaki, T.
Internal flow mechanism in filter cakes
AIChE, J., vol.15, no.3, p.405-409, 1969

[7] Tiller, F.M., Yeh, C.S.
The role of porosity in filtration. Part XI: filtration followed by expression
AIChE. J., vol.33, no.8, p.p. 1241-1257, 1987

[8] La Heij, E.J., Herwijn, A.J.M., Coumans, W.J., Kerkhof, P.J.A.M.
Filtration and expression behaviour of sewage sludge
presented at the AIChE annual meeting November 1992, Miami Beach.

CHARACTERIZATION OF SEWAGE SLUDGES; FUNDAMENTALS AND RESULTS

Arend J.M. Herwijn and W.Jan Coumans

(Laboratory of Separation Technology, Dept. of Chemical Engineering, Eindhoven University of Technology, P.O.Box 513, 5600 MB Eindhoven, the Netherlands)

SUMMARY

An overview is given of a set of sludge characteristics. This set, which can be considered as a sludge fingerprint, is estimated to be of some relevance both for thermal and mechanical dewatering processes. Four different types of sludges have been studied, whereby flocculation was carried out under standard conditions in the laboratory. Some typical results are presented and some preliminary conclusions will be given with respect to the mechanical dewatering process and its relation with the preceding flocculation process.

1. INTRODUCTION

In waste water treatment plants the dewatering of sludges by chamber filtration presses, sieve belt presses and centrifuges appears to be a unit operation which is very badly understood [Starkenburg and Rijs, 1991]. The main reason for this is the complexity of the sludge material. By no means sludges can be considered as well defined systems with "beautiful" and constant properties. Numerous chemical components might be encountered, a great variety of shape and size of colloidal and non-colloidal solid particles may be found. Both flocculated and unflocculated particles may be deformable and sensitive to shear stresses and may be disrupted in mixing and stirring processes. Moreover, when flocculated solid particles are collected in a filtration process the formed filter cake appears to be highly deformable as well. This means that by exerting some mechanical forces to the cake material the porous structure collapses and a lot of water remains entrapped within the cake. It is believed that this mechanism is determining to a high extent the attainable final dry solids content in a mechanical dewatering process.

Nowadays there are environmental and economical reasons to strive for a higher dry solids content of sludge cakes. This is explained in more detail elsewhere (La Heij and Kerkhof, 1993). It will be clear that achieving a better dewatering process requires better knowledge of the fundamentals, better design rules for the dewatering equipment and better control strategies.

It is common practice in process technology research to perform studies with well defined model systems having all the relevant properties of the real system. However with respect to sludges this is not an easy approach, because till now the ruling properties are not known

sufficiently well.
In this study it is the aim to establish a set of sludge characteristics. A set that may be considered as a *fingerprint* of the sludge. Subsequently several real sludges (see section 3) are to be characterized; finally the characteristics are to be cross (cor)related and are also to be (cor)related to the dewatering behaviour of the sludges in well defined laboratory tests and in practical plant dewatering equipment. This study is carried out in the Sludge Dewatering Project Team and therefore this paper is closely related to a second contribution from this team to this workshop (La Heij and Kerkhof, 1993).

2. SURVEY OF CONSIDERED PROPERTIES

The sludge fingerprint is based on properties that can be divided into the following classes:
- Origin and history
- Composition
- Thermal properties
- Colloidal properties
- Dewatering properties

The properties belonging to each class are summarized below.

History
- origin of waste water (domestic/industrial)
- type of waste water treatment plant
- typical information about plant operation

Composition:
- Dry solids content
- Ash content
- ATP content
- pH
- Electrical conductivity

Thermal properties:
- Sorption isotherms at several temperatures
- Isothermal drying curves (TGA/DTA)
- Freezing curves (DSC)
- Bond enthalpy of water in sludge

Thermal properties are also of immediate importance for thermal dewatering by means of drying processes.

Colloidal properties:
- Sludge Volume Index (SVI) of unflocculated and flocculated sludge
- Particle size distribution and morphology
- Electro Sonic Analysis signal (related to zeta-potential)
- Optimum dosage of flocculant
- Concentration of flocculant in filtrate
- Strength of flocs from rheology

Dewatering properties:
- Specific cake resistance and porosity (permeability)
- Cake compressibility (mechanical properties of cake)
- Dry solids content of filtration cake
- Vacuum suction time (VST)
- *Capillary Suction Time (CST)*

It may be expected that these characteristics are closely related to the real mechanical dewatering processes in water treatment plants by means of chamber filtration press, sieve belt press and centrifuges.

3. ORIGIN AND HISTORY OF SLUDGES INVESTIGATED

Different types of sludges may be distinguished depending on the origin of the waste water and on the type of waste water treatment plant. Waste water entering the sewer system origins from households (domestic sewage) and/or from industries (industrial sewage).
The following main types of sludges, depending on the waste water treatment, are recognized:
- Primary sludge, which is separated from the incoming waste water in the primary settling tank.
- Secondary sludge, withdrawn from the secondary settling tank. In the preceding step this sludge has been submitted to a biological treatment in an aeration tank, where the organic matter is oxidized.
- Digested sludge or anaerobically stabilized sludge. In a digestion process the sludge is stabilized by anaerobic metabolic processes, in which organic carbon compounds are converted into biogas (methane and carbon dioxide).

In this study four sewage sludges, originating from four different waste water treatment plants, have been characterized. Below some typical characteristics concerning origin and history of the different sewage sludges are listed.

TABLE 1. Survey of sludges investigated

Name of plant	domestic/ industrial	primary, secondary	digested, undigested
Mierlo	60/40	mixture	undigested
de Lage Zwaluwe	100/0	secondary	undigested
Amsterdam-East	100/0	mixture	digested
Veghel	35/65	secondary	undigested

It should be mentioned that all above listed sludges are flocculated in the laboratory, because the industrial conditions of flocculation are not known sufficiently well. Under laboratory conditions the flocculation conditions are better known and at least the same for all sludges. Moreover, the flocculation process appears to be a very critical operation which affects the

dewatering properties of the sludge to a great extent. An ill defined flocculation process would therefore cause a lot of problems in understanding the dewatering properties of sludges.

4. CHARACTERIZATION METHODS

4.1 COMPOSITION

To determine the **dry solids content** of a sewage sludge or a filter cake the sample is dried in a furnace at 110 ^{0}C during 24 hours. The addition of inert materials (e.g. during flocculation) causes an artificial augmentation of the dry solids content. By comparing the effect of certain treatments (e.g. flocculation) on dewatering properties in this study the water removal was related to the *initial* dry solid content of the sludge.
The **ash content** is related to the inorganic fraction of the solids in the sludge and is determined by burning the dried sample at 600 ^{0}C during 30 minutes.
The **Adenosine TriPhosphate (ATP) content** of a sewage sludge sample is used as a measure for the viable biomass. The determination of the ATP content is based on the luminescent reaction of ATP with luciferase, in which light production is proportional to ATP present [Patterson et al., 1970].
The **pH** and the **electrical conductivity** are ordinary laboratory routines and do not need further introduction here.

4.2 THERMAL PROPERTIES

4.2.1 Isothermal drying curves (TGA/DTA)

Knowledge about the solid-water bond strength in sludge as a function of the moisture content enables the prediction of the maximum theoretically feasible dry solids content in a certain dewatering process. The solid-water bond strength can be obtained from isothermal drying curves and from water vapour isotherms.
With thermogravimetric analysis (TGA) the mass loss of a sludge filter cake, due to vaporization of water at a constant temperature of 60 °C, is measured continuously. In this way an isothermal drying curve is obtained. From differential thermal analysis (DTA) the heat flow required for the vaporization of water can be calculated. The TGA/DTA equipment provides the possibility to carry out TGA and DTA simultaneously. The ratio between vaporization rate (in kg/s), calculated from the TGA experiments, and heat flow to the sample (in J/s) is equal to the enthalpy of vaporization of water present in the sample (in J/kg). The bond enthalpy is defined as the difference between the actual measured enthalpy of vaporization and the enthalpy of vaporization of pure water. With this technique the bond enthalpy can be calculated as a function of the sample moisture content. Moreover, from the falling rate period of drying curves moisture diffusion coefficients can be derived [Coumans, 1987].

4.2.2 Water vapour (de)sorption-isotherms at different temperatures

A water vapour (de)sorption-isotherm of a substance is the equilibrium relationship between the amount of water in the substance and its thermodynamic water activity at a constant

temperature. Water vapour desorption isotherms of sludge cake samples were determined with the conventional technique of vacuum exsiccators with (super)saturated aqueous salt solutions to control the water activity. The equilibrium data for the water activity of these solutions were taken from the tables given in literature [Greenspan, 1977]. For keeping a constant temperature during equilibration the exsiccators were positioned in a water bath. In an experiment twelve sludge cake samples were placed in twelve exsiccators, each with their own water activity and covering the whole range of wateractivities between 0 and 1. Equilibrium was assumed if two subsequent sample weighings gave the same results. At reaching equilibrium conditions, the moisture content of the samples was determined and the desorption isotherm was constructed. In this way desorption isotherms were measured at three different temperatures. From the three isotherms, the differential enthalpy of wetting as a function of the moisture content can be calculated by applying the Clausius-Clapeyron equation. The differential enthalpy of wetting corresponds thermodynamically with the bond enthalpy. In Figure 1 the results of both techniques, carried out with Amsterdam sludge flocculated with 27% $FeCl_3$, are given.

The discrepancy between the two curves for moisture contents lower than 0.2 kg water/kg dry solids is due to the different experimental conditions: the moisture content of the sample in the exsiccator is determined in an equilibrium situation, whereas in the TGA equipment no equilibrium condition occurs. Moreover desorption isotherms were not measured at very low water activities (< 0.05). So the bond enthalpy calculated in in this region are extrapolated values which might be unreliable.

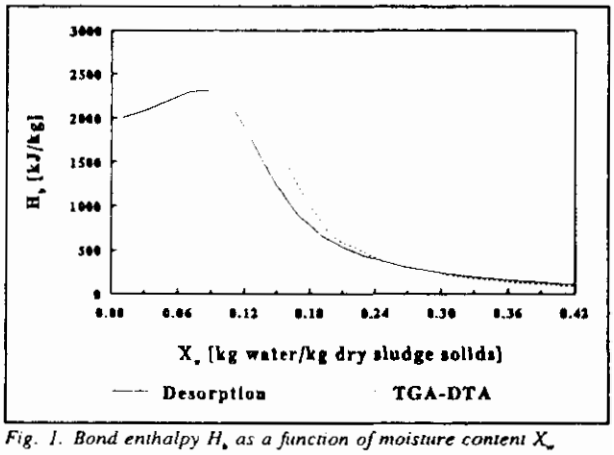


Fig. 1. Bond enthalpy H_s as a function of moisture content X_w

Moreover, it can be concluded that the bond enthalpy starts to deviate significantly from zero at a moisture content of about 0.4 kg water/kg dry solids. In sludge filter cakes the moisture content amounts about 4 kg water/kg solids (=20%DS), which means that about 90% of the water in the filter cake is present as *free water* and should, from this point of view, be removable by mechanical dewatering processes. The remaining 10% having a higher bond enthalpy, the socalled *bound water*, can only be removed in e.g. drying processes.

4.3 COLLOIDAL PROPERTIES

4.3.1 Particle size distribution

The "image analysing technique" has been used to study the particle size distribution of a sewage sludge sample. The experimental equipment consists of an optical microscope, camera and computer. A picture of a sludge sample is registrated and digitalized and shown on the screen of the computer system. The surface area of the particles is determined and converted into an effective diameter.

The frequency of the effective diameter is based here on the number of the particles with that

size. The measured cumulative particle size distribution is approximated by the Harris equation F(x) [Svarovsky, 1990]:

$$F(x) = 1 - \left[1 - \left(\frac{x}{x_0}\right)^a\right]^b \qquad (1)$$

where x_0 is the maximum diameter, a and b are constants. The Harris equation, as represented above, describes an "undersize" cumulative frequency distribution, so F(x) indicates the fraction of particles with a diameter smaller than x.

The particle size distribution of sewage sludge samples, flocculated with different types of flocculants and with different dosages of flocculant, are determined and evaluated according to the above method. In Figure 2, typical particle size distributions are given for sewage sludges flocculated with different polyelectrolyte (Rohafloc KF975) dosages. The effect of an increasing amount of polyelectrolyte is the shifting of the distribution curves towards greater diameters.

The median diameter is easily found at F(x)=0.5. The median diameter appears to be a good characteristic to indicate the particle size. Typical values for the median diameter are:
- 5-10 μm for particles in unflocculated sludges;
- 8-20 μm for particles in sludges flocculated with $FeCl_3$;
- 500-2000 μm for particles in sludges flocculated with polyelectrolyte (Figure 2).

The particle size also depends on the type of flocculant used and on the stirring and mixing conditions during the flocculation process.

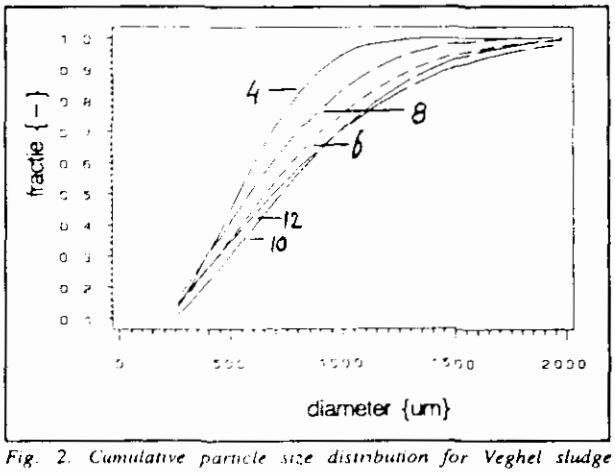


Fig. 2. Cumulative particle size distribution for Veghel sludge flocculated with different dosages polyelectrolyte KF975 (in g/kg ds)

4.3.2 Strength of flocs

During the filtration and expression of sewage sludge shear stresses are exerted on the sludge particles. Sewage sludge is a colloidal dispersion and it is interesting to study its rheological properties. A Searle type coaxial cylinder rheometer is used to determine the rheological behaviour of sewage sludges. A sewage sample is introduced into the small gap between two cylinders. The inner cylinder rotates and the outer cup remains stationary. In an experiment, the angular velocity of the spindle is increased in 15 steps until the maximum speed and is subsequently decreased. The torque needed to maintain the angular velocity is measured and converted to a shear stress. The result of such an experiment is called a rheogram. A typical rheogram of a sludge flocculated with $FeCl_3/Ca(OH)_2$ is illustrated in Figure 3. It is notable that the ascending and descending curves do not coincide. This phenomenon is called thixotropy. It physically means that sludges possess an internal structure which breaks down

as a function of time and shear rate. The surface area between the two curves can be interpreted as the dissipated power per unit volume and is a measure for the strength of particles or flocs.
Unflocculated sludges do not show thixotropic behaviour. Sludges flocculated with $FeCl_3/Ca(OH)_2$ and polyelectrolyte exhibit a maximum value of the thixotropy at a certain dosage.

Rheological behaviour of sewage sludges can be interpreted as pseudoplastic flow:

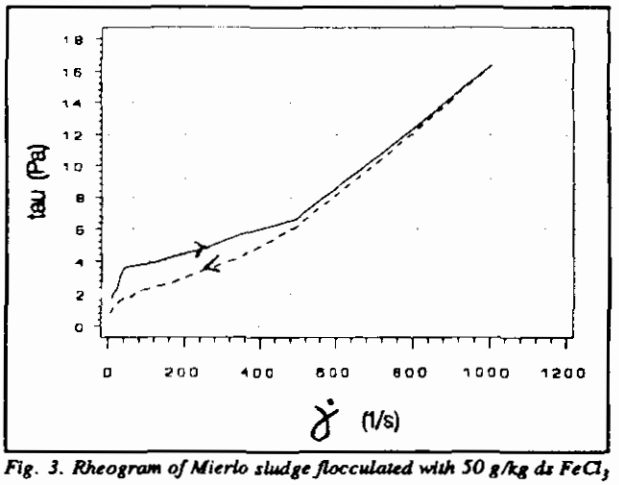


Fig. 3. Rheogram of Mierlo sludge flocculated with 50 g/kg ds $FeCl_3$

$$\tau = \tau_0 + k(\dot{\gamma}, t)\dot{\gamma} \qquad (2)$$

τ_0 is an initial characteristic shear stress and $k(\dot{\gamma},t)$ is called the plastic viscosity, which depends on time and shear velocity.
The viscosity k as a function of the shear velocity $\dot{\gamma}$ is calculated from the measured rheogram. The plastic viscosity for flocculated sludges decreases with increasing shear velocity. The plastic viscosity can be determined as a function of time in a stationary shear experiment. It appears that for flocculated sludges the viscosity decreases with time. The decline in viscosity is stronger for higher dosages of flocculant ($FeCl_3$ and polyelectrolyte). Unflocculated sludges show no reduction of viscosity as a function of time.

4.3.3 Zeta potential

Unflocculated sludge particles are negatively charged. A measurable parameter which is proportional to the surface charge density of particles is the zeta potential. The zeta potential, often used to characterize the electrostatic stability of colloidal suspensions, can be determined with the socalled electro-acoustic technique (MATEC). In this technique the colloidal suspension is submitted to an alternating electric field. The relative motion between the particles and the liquid generates a sound wave at the frequency of the electric field. This effect has been termed the Electrokinetic Sonic Amplitude (ESA), which is strongly related to the zeta potential of the particles in the colloidal suspension.
In Figure 4 a schematic diagram of the electro-acoustic cell is given. The vessel is stirred and includes sensors for pH, temperature, conductivity and electro-acoustic measurements. The zeta potential is determined from the measured electro-acoustic data. It is possible to perform automatic volumetric titration experiments. This equipment is very suitable for studying the flocculation mechanism because continuous measurement of the ESA-signal is possible during titration of flocculant to a sludge.
A typical example of the ESA signal as a function of the $FeCl_3$ concentration in sewage sludge is given in Figure 5. At a certain dosage a sudden change of the ESA signal occurs due to adsorption effects. Iron hydroxide complexes adsorb at the surface of the

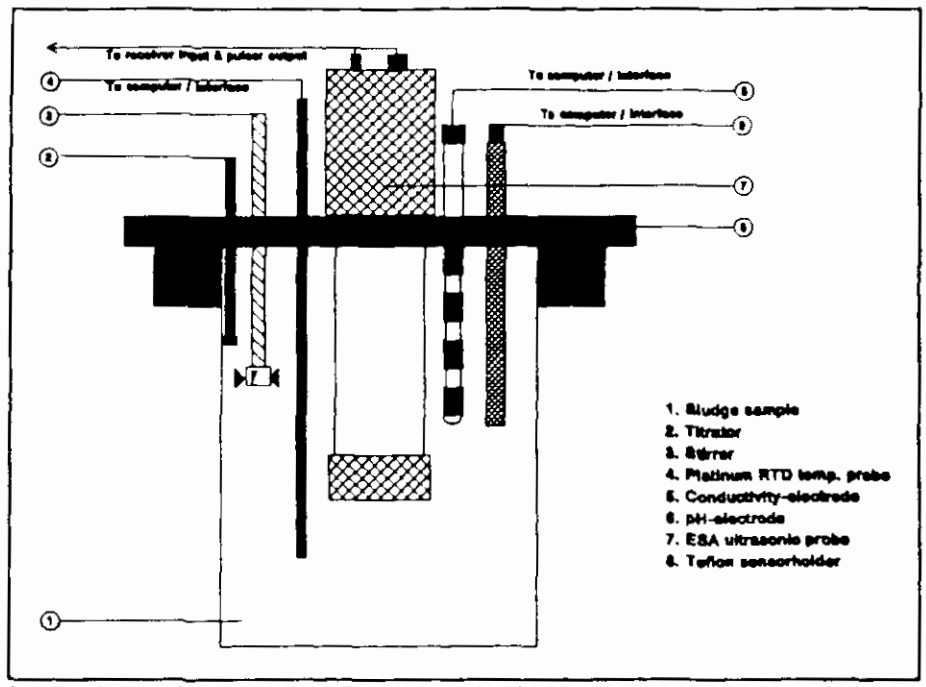


Fig. 4. Schematic diagram of the MATEC ESA sample cell

sludge particles. Sludge particles surrounded by layers of metal hydroxide complexes stick to each other and so flocs are formed. At a certain dosage of flocculant the adsorption of iron hydroxide complexes causes a change of the electric charge of the particles. The ESA-plots and more specific the charge transition point can be considered as sludge characteristics. The charge reversal point (ESA = 0) corresponds theoretically to a number of bulk properties of the suspension: maximum dewaterability and minimum electrostatic stability. In the experiments carried out with $FeCl_3$, the dosage where ESA is zero often corresponds with a minimum specific cake resistance.

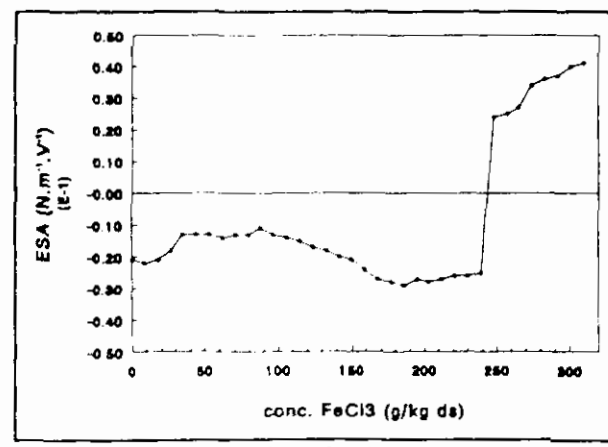


Fig. 5. Measured ESA-signal as a function of concentration $FeCl_3$ in Mierlo sewage sludge

Unfortunately, sofar it seems that the MATEC-ESA system does not provide a reliable and suitable technique for studying sludge floc formation processes induced by organic flocculants.

4.4 DEWATERING PROPERTIES

4.4.1 Specific cake resistance and cake permeability

The solid-liquid separation of sewage sludge can be subdivided into a filtration phase and an expression phase [La Heij and Kerkhof, 1993]. In order to study the solid-liquid separation process and to characterize the dewatering behaviour of sludges a filtration-expression cell has been developed. A schematic diagram of this cell is given in Figure 6.

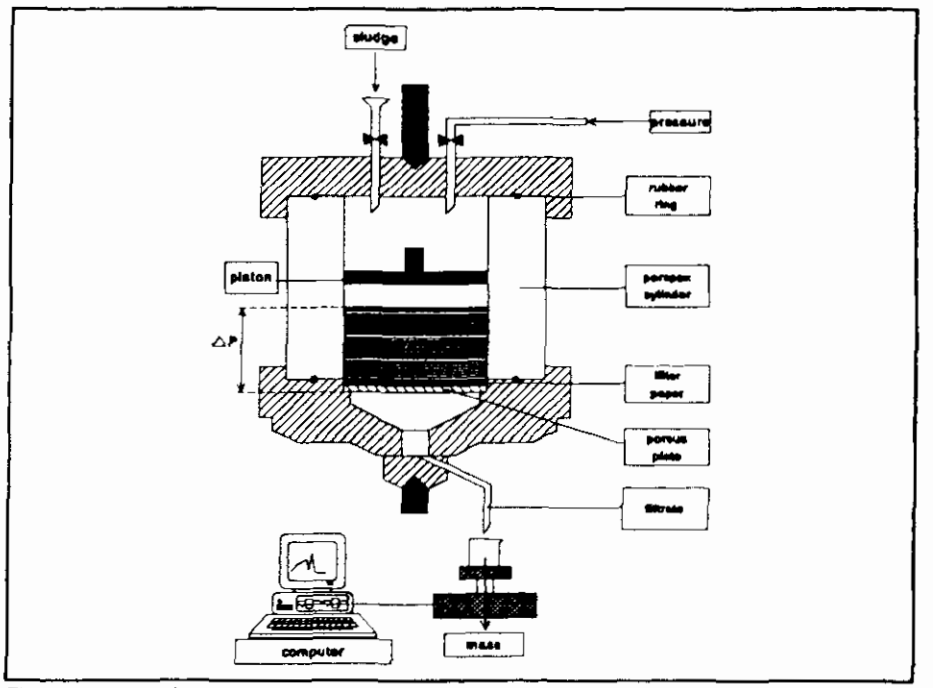


Fig. 6. Schematic diagram of the filtration-expression cell

At the beginning of the experiment a gas pressure is suddenly exerted on the sludge sample. The gas pressure is the driving force for the solid-liquid separation. A filter cake is built up and the filtrate is collected in a beaker glass positioned on a balance. The balance is connected to a computer, which registrates continuously the weight of the filtrate (and thus also the filtrate volume). With this experimental set up it is possible to carry out experiments under different process conditions such as gas pressure, type of flocculant, flocculant dosage and amount of sewage sludge (or final cake thickness). In the Figures 7 and 8 typical results are given for sewage sludges flocculated with respectively $FeCl_3$ in combination with $Ca(OH)_2$ and polyelectrolyte. The experimental results are fitted with the integrated form of Darcy's law, in which filtration time t is related to filtration volume V:

$$t = \frac{\alpha \mu c}{2A^2 \Delta P} V^2 + \frac{\mu R_m}{A \Delta P} V \qquad (3)$$

From the fitted equation, the average specific cake resistance α can be calculated. Knowing the average porosity ϵ of the cake, the cake permeability K can be calculated according to:

$$K = \frac{1}{\alpha \rho_s (1-\epsilon)} \qquad (4)$$

Though the above equations are valid only for incompressible filter cakes they still can be used for characterization of the compressible sludge cakes [La Heij and Kerkhof, 1993]. For modelling purposes and to obtain a better understanding of the dewatering process of a compressible cake also a socalled *compression-permeability cell* has been developed [La Heij and Kerkhof, 1993].

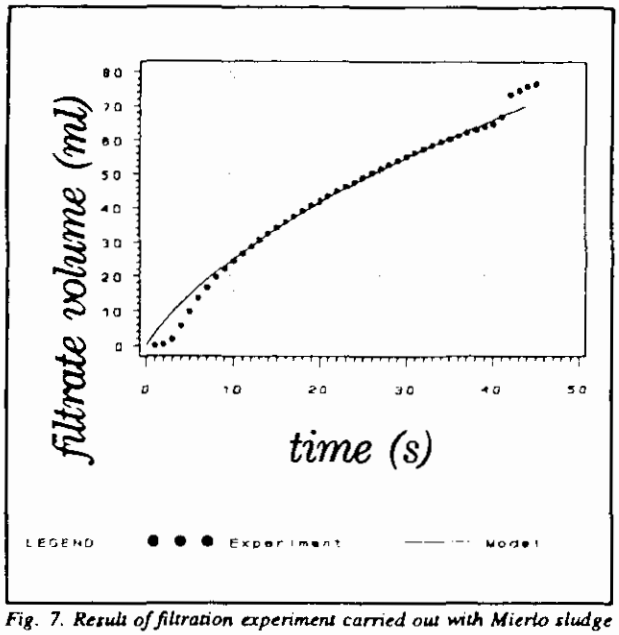


Fig. 7. Result of filtration experiment carried out with Mierlo sludge flocculated with 9 wt% $FeCl_3$ and 20% $Ca(OH)_2$ on dry solids base

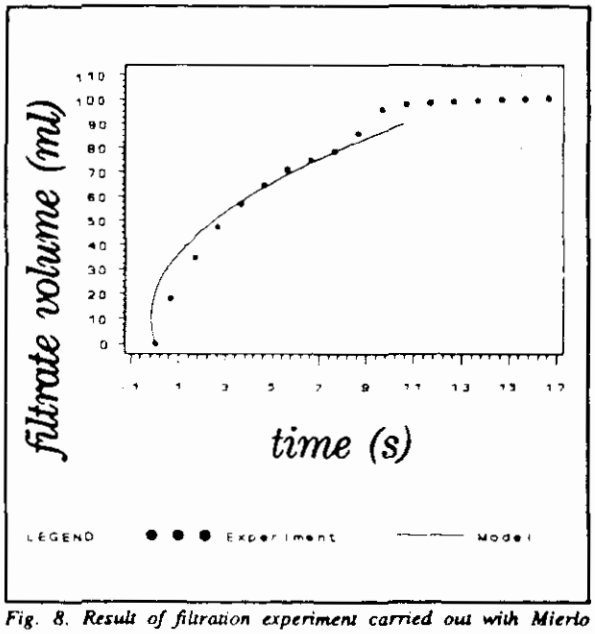


Fig. 8. Result of filtration experiment carried out with Mierlo sludge flocculated with 0.9 wt% polyelectrolyte on dry solids base

In both experiments (Figures 7 and 8) a sudden change in filtrate volume can be observed (40 s respectively 9 s) due to the formation of cracks in the filter cake.
Typical differences between the filtration behaviour of sludges flocculated with respectively $FeCl_3/Ca(OH)_2$ and polyelectrolytes are:
- The dosages of $FeCl_3$ and $Ca(OH)_2$ needed to obtain a good dewatering result is about ten times higher than the dosage of polyelectrolyte.
- The average specific cake resistance for sludges flocculated with $FeCl_3/Ca(OH)_2$ is about five to ten times smaller than the average specific cake resistance for sludges flocculated with polyelectrolyte.

4.4.2 Modified Filtration Test

With the Modified Filtration Test (MFT) filtration experiments are carried out with a constant under pressure of 0.5 bar [Heide and Kampf, 1978]. In Figure 9 a schematic

drawing of the MFT-equipment, consisting of three parallel filtration tubes, is given. In this set up three experiments can be carried out simultaneously.

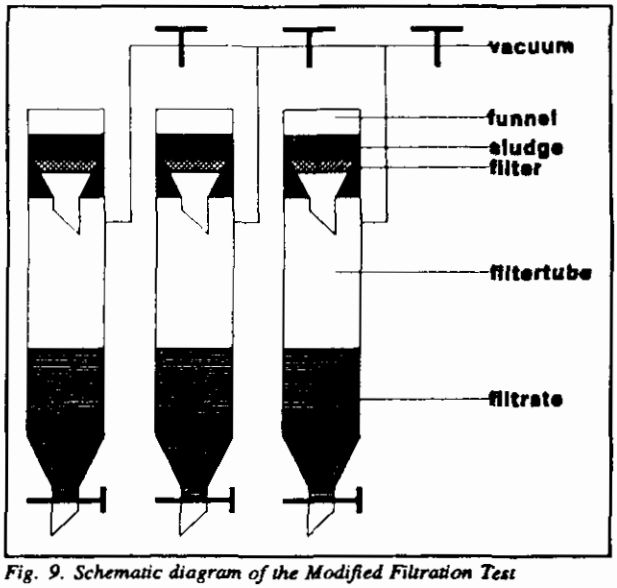


Fig. 9. Schematic diagram of the Modified Filtration Test

A flocculated sludge sample of 100 ml is introduced into the Büchner funnel. By immediately applying the under pressure the filtration process starts and liquid starts flowing into the filter tube. The filtrate volume can be read from a scale on the tube. After the cake has become somewhat dry, a plastic foil is positioned on top of the cake. Next a water layer of about 3 cm is applied on the foil and the expression phase starts. After 10 minutes the experiment is stopped. From this test the following dewatering characteristics can be determined:

1. **"Vacuum" suction time (VST)**, which is defined as the time needed to collect 60 ml of filtrate at an under pressure of 0.5 bar. The VST is a measure for the filtration *rate*.
2. **Final dry solids content** of the sludge cake based on total solids (sludge solids plus flocculant plus other additives).
3. **Water content of the sludge cake**, expressed in kg water per kg initial dry solids in the sludge sample. This moisture content is corrected for the dry solids from additives and provides a better comparison of the effect of e.g. the nature and amount of flocculant on the dewatering process.
4. **Optimum dosage of flocculant** (which can also be considered as a colloidal property) is defined as the dosage of flocculant which yields the lowest water content of the sludge cake.

The influence of type and dosage of flocculant on the dewatering characteristics can be studied easily with this simple experimental device.

4.4.3 Capillary Suction Time

The Capillary Suction Time (CST) device is a simple instrument to determine the dewaterability of sewage sludges (Figure 10). At the start of an experiment, sludge (2) is poured into the cylindric reservoir (1), resting on the filter paper (6). Under the influence of the capillary suction of the fine capillary-porous paper and the gravity force, filtrate is drawn out of the sludge to saturate progressively a greater
area of the filter paper, causing the liquid front to advance outwards from the centre. When the filtrate front reaches the first electrode (4), the timer (5) starts. When the filtrate reaches the second electrode, the timer stops. The capillary suction time is then read directly from the timer.

The lower the CST the better is the filtrability of the sludge.

The CST-test can be considered as a gentle filtration process where sludge cakes are exerted to very low forces.

Results of experiments carried out with unflocculated sludges show a bad reproducibility. The CST method appears to be very suitable and reproducible for sludges flocculated with $FeCl_3$. The instrument appears to be not appropiate for sludge samples consisting of relatively large particles (500-2000 μm), e.g. sludge samples flocculated with polyelectrolytes.

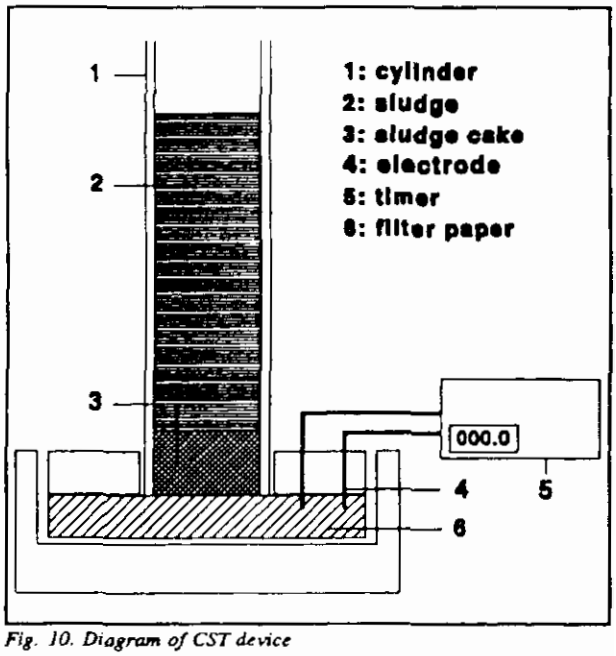


Fig. 10. Diagram of CST device

4.4.4. Sludge Volume Index

The sludge volume index (SVI) is a measure for the sedimentation *rate* of sludge particles. The SVI is defined as the volume taken by sludge particles after 30 minutes of sedimentation in a sewage sludge sample containing 1 g/l dry solids. The SVI is frequently used in waste water treatment plants as a sludge characteristic.

5. CONCLUSIONS

This research is still in progress and unfortunately not all experimental results are evaluated yet, nor are (cor)relations between characteristics fully studied so far. This means that only some preliminary conclusions, valid for all four sludges investigated, can be drawn here:

- Dewatering characteristics appear to be strongly dependent on flocculation conditions (nature and dosage of flocculant, intensity and duration of mixing and stirring). This conclusion, perhaps an open door to many experts, is still emphasized here once more. It is believed that a bad sludge dewatering process, also in real plant practice, may be caused by bad flocculation conditions in the first place. Therefore every fundamental study of dewatering characteristics will soon become a study of flocculation phenomena.
- For obtaining optimum flocculation, and thus the highest dewatering effect in the shortest time, the following characterization tests could be used for controlling the dosage of flocculant:
    - Filtration-expression test
    - Modified filtration test
    - Capillary Suction Time test
    - Rheology test
    - Image Analyzing test
- By preference the Modified filtration test should be used because of its simplicity and because it gives information both about the final moisture content of the sludge cake and the dewatering rate.
- Sludge volume index, ATP, pH and electric conductivity do not show any correlation with the dewatering characteristics and can *not* be used for optimum flocculant dosage. Due to

analytical problems it is not clear so far, whether the flocculant concentration in the filtrate could also be used as an indicator for the quality of the flocculation process or not.
- By using polyelectrolytes as flocculant both degree and rate of sludge dewatering is higher than by using $FeCl_3/Ca(OH)_2$.

ACKNOWLEDGEMENTS

This research has been financially supported by the Netherlands Institute of Inland Water Management and Waste Water Treatment (RIZA) and the Netherlands Foundation of Applied Waste Water Research (STOWA). The contributions of the other members of the Sludge Dewatering Project Team at Eindhoven University, namely E.J. La Heij, P.J.A.M. Kerkhof, P.M.H. Janssen, G.D. Mooiweer and many students, are gratefully acknowledged.

LIST OF SYMBOLS

a	constant	-
A	filter area	m^2
b	constant	-
H_b	bond enthalpy	J kg^{-1}
k	plastic viscosity	Pa s
K	permeability	m^2
ΔP	pressure difference	Pa
R_m	filtermedium resistance	m^{-1}
t	time	s
V	filtrate volume	m^3
x	diameter	m
x_0	maximum diameter	m
X_w	moisture content	kg water(kg initial dry solids)$^{-1}$

Greek symbols

α	specific cake resistance	m kg^{-1}
ϵ	porosity	-
μ	viscosity filtrate	Pa s
τ	shear stress	Pa
τ_0	yield stress	Pa
$\dot{\gamma}$	shear velocity	s^{-1}

LITERATURE

Baskerville, R.C., Gale, R.S.,
A simple automatic instrument for determining the filterability of sewage sludges
Water Pollution Control, no.3, 233-241, 1968

Coumans, W.J.,
Power law diffusion in drying processes
Ph. D. thesis, Eindhoven University of Technology, Eindhoven, 1987

Greenspan, L.
Humidity Fixed Points of Binary Saturated Aqueous Solutions
J.Res.Nat.Bur.Standards, Vol 81A, 89-96, 1977

Heide, B.A., Kampf, R.,
De MFT-methode als kenmerk voor de ontwaterbaarheid van slib
H_2O, vol.11, 1978

La Heij, E.J., Kerkhof, P.J.A.M.
Fundamental aspects of sludge filtration and expression
Japanese-Dutch Workshop , 17-23 October, 1993, Miyazaki, Japan

Patterson, J.W., Brezonik, P.L., Putnam, H.D.
Measurement and significance of Adenosine Triphosphate in Activated Sludge
Environmental Science & Technology, vol. 4, no.7, 569-575, 1970

Starkenburg, W.van, Rijs, G.B.J.
Needs for research in the future
First Dutch-Japanese workshop on the treatment of municipal waste water, 8-11 April 1991, Heelsum, the Netherlands, part II, nr.25

Svarovsky, L.
Solid-liquid separation
Butterworths, London, 3rd edition 1990

FILTRATIE EN PERSING VAN ZUIVERINGSSLIB; MODELVORMING

E.J. La Heij
Laboratorium voor Scheidingstechnologie, vakgroep Chemische Proceskunde, faculteit Scheikundige Technologie, Technische Universiteit Eindhoven, 5600 MB, Eindhoven

Samenvatting

Het filtratie en persingsgedrag van zuiveringsslib zal worden besproken. Vanwege de toename in kosten voor gecontroleerde dumping en transport en strengere milieu wetgevingen, wordt de vraag naar de reductie van het slibvolume steeds groter. Filtratie en persing zijn de goedkoopste ontwateringstechnieken en het is daarom van belang zoveel mogelijk water met mechanische ontwatering te verwijderen. Relatief hoge eind droge stof gehaltes 35-40 gew% zijn reeds bij drukken van 300-400 kPa en optimale flocculatiecondities te bereiken; echter bij hoge mechanische drukken (6-10 MPa) kunnen droge stof gehaltes van ± 60 gew% worden bereikt. Verder wordt de modellering van de ontwatering besproken; model en experiment vertonen acceptabele overeenkomst.

Inleiding

De produktie van slib van waterzuiveringsinstallaties neemt ieder jaar nog toe; de produktie was in 1990 310.000 ton per jaar op droge stof basis en de verwachting voor 2000 is 400.000 ton per jaar. Het meeste slib wordt nog altijd afgezet in de landbouw of voor de produktie van compost. De hoeveelheden nemen echter af en er wordt steeds meer slib gedumpt. Slechts enkele procenten van de totale hoeveelheid slib wordt verbrand. De afzet van slib in de landbouw zal de komende jaren alleen maar minder worden vanwege de strengere eisen wat betreft de toegestane hoeveelheden zware metalen. Kosten voor transport en dumping nemen steeds meer toe en het aantal dumpplaatsen neemt ook af vanwege strengere milieumaatregels. Afname van de hoeveelheid van water in slib is daarom van groot belang. Voor transport om kosten te verlagen; voor dumping om het volume te verkleinen en voor verbranding om onder autotherme condities het slib te kunnen verbranden. Het droge stof gehalte van slib voor ontwatering is gemiddeld 2-4 gew%, terwijl mechanische ontwatering in de praktijk met zeefbandpersen 17-25 gew% en voor filterpersen 25-30 gew% oplevert. Indien een eind droge stof gehalte van 40 gew% in de toekomst wordt bereikt is het mogelijk om per jaar ongeveer Fl 80.000.000 te besparen op de verwerkingskosten (hierbij is de toename van de slibproduktie meegerekend).

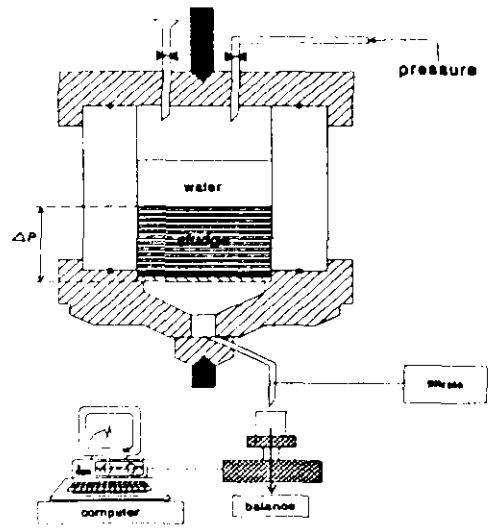
Laboratorium experimenten

Om het filtratie en persgedrag te bestuderen zijn een aantal laboratorium opstellingen zeer nuttig, die hieronder in het kort worden besproken.

De filtratie-persings cel

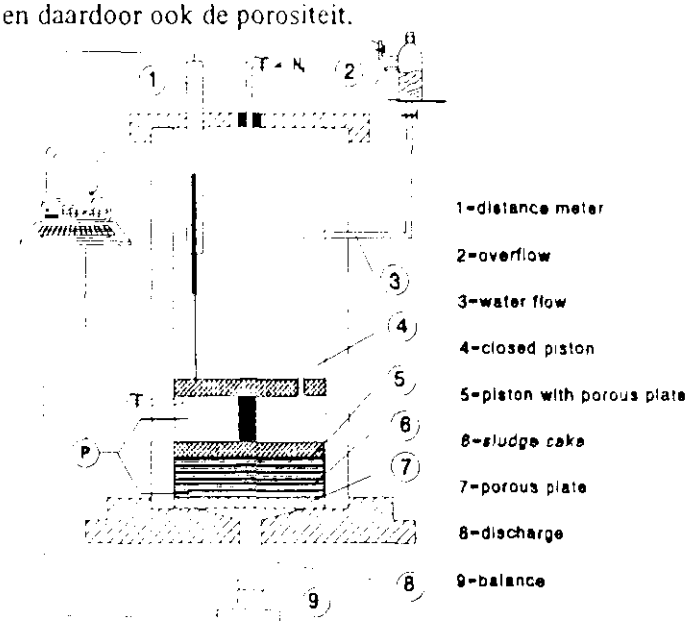
De cel, zoals getoond in figuur 1, bestaat uit een perspex cilinder met een poreuze bodemplaat met daarop een filtreerpapier. Het geflocculeerde slib wordt nu in de cel gegoten en vervolgens wordt er een zuiger op geplaatst. Op deze zuiger wordt een gasdruk aangelegd, zodat die gasdruk de

mechanische druk bepaalt. Er zal bij dit experiment eerst een koek worden gevormd tijdens de filtratie fase en de koek wordt uitgeperst tijdens de pers fase.



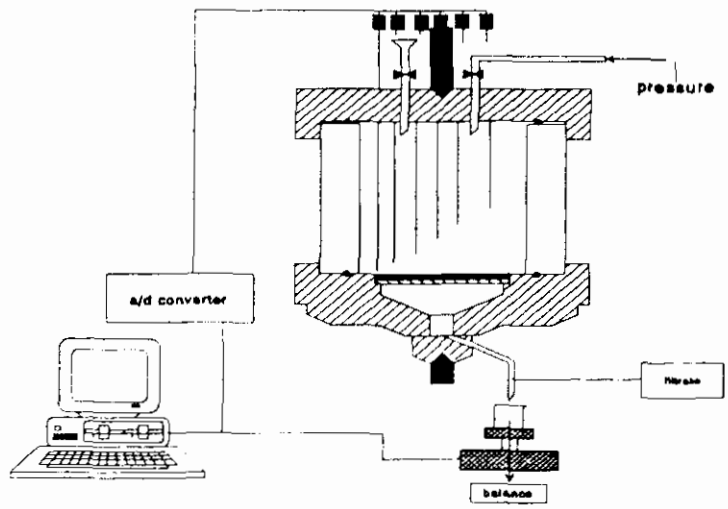
Figuur 1. *Schematische weergave van filtratie-persings cel.*

De compressie-permeabiliteits (CP) cel
Voor de modellering van het filtratie en persgedrag zijn de relaties tussen permeabiliteit, porositeit en compressiedruk van groot belang. De CP-cel is schematisch weergegeven in figuur 2. Het bestaat wederom uit een perspex cilinder met een poreuze bodemplaat, waarop een filtreerpapier is geplaatst. Nadat geflocculeerd slib in de cel is gegoten, wordt een dubbele zuiger in de cilinder geplaatst. De onderste zuiger is poreus, de bovenste gesloten. Door een gasdruk aan te legger op de bovenste zuiger, wordt de koek uitperst. De druk van de zuiger bepaalt de compressiedruk. Door nu een water laag tussen de twee zuigers aan te brengen waarop een klein beetje gasdruk wordt gezet, kan de vloeistofstroom door de koek worden gemeten. Door de vloeistofstroom en de vloeistofdruk te meten kan de permeabiliteit worden uitgerekend. Met een verplaatsingsopnemer verbonden met de zuiger is de koekdikte bekend en daardoor ook de porositeit.



Figuur 2. *Schematische weergave van compressie-permeabiliteits (CP) cel.*

De drukverdelingscel (figuur 3)
Deze cel is hetzelfde als de normale filtratie cel, maar heeft een aantal capillairtjes met verschillende lengtes, die zijn verbonden met drukopnemers. Met behulp van deze capillairtjes is het mogelijk om op verschillende hoogtes in de filterkoek de vloeistofdruk te meten. Door een mengsel van glycerol en klei (dat als zuiger dient) op de koek te plaatsen kan de koek worden uitgeperst.



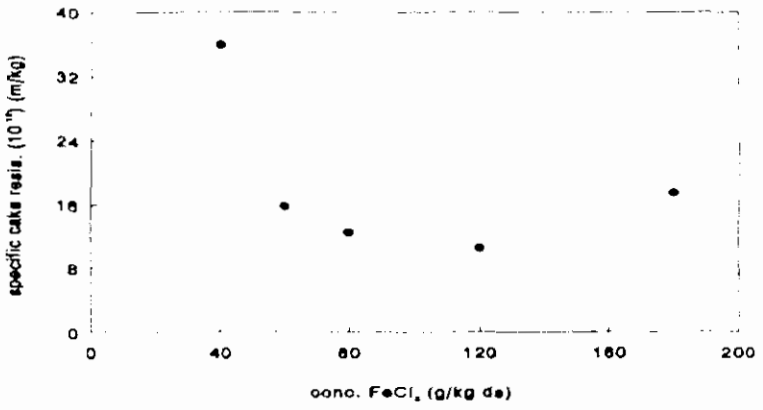
Figuur 3. *Schematische weergave van drukverdelings cel.*

Filtratie en persexperimenten

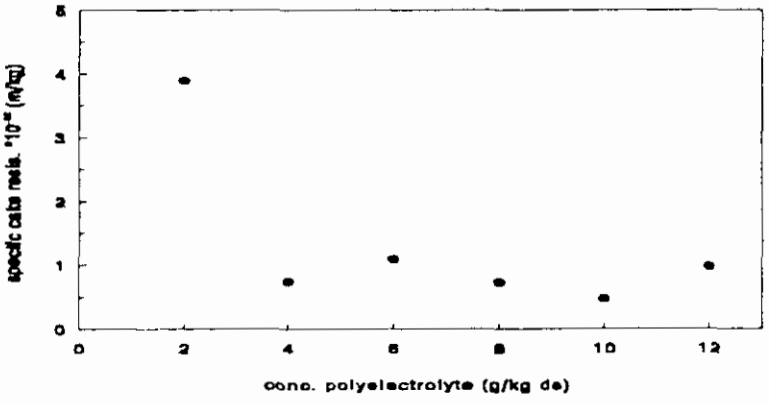
Een eerste interpretatie van dit filtratie curven is door middel van een gemiddelde specifieke filtratieweerstand α:

$$\alpha = \frac{R_c}{w}$$
$$R_c = \frac{\Delta p_l}{\eta q_l} = \frac{L_c}{K} \qquad (1)$$

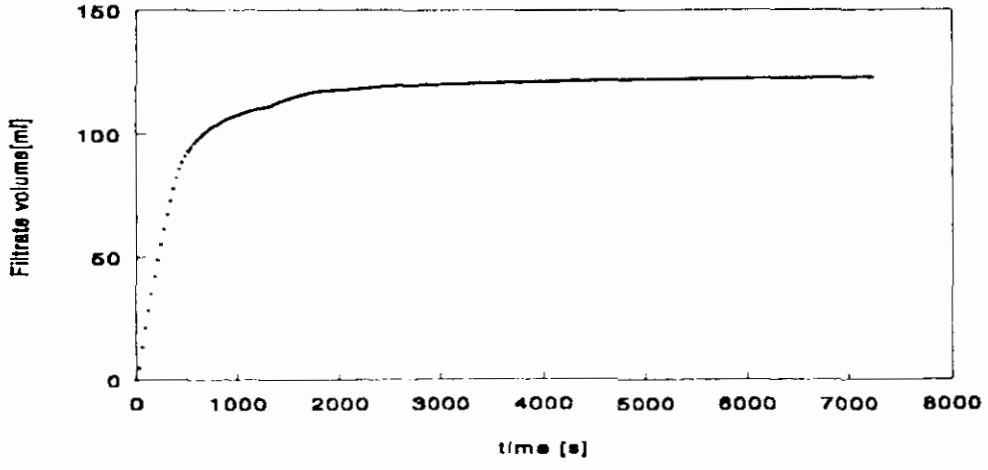
waarbij R_c de koekweerstand is , w de hoeveelheid vaste stof per oppervlakte eenheid, Δp_l de filtratiedruk, η de vloeistof viscositeit, q_l de superficiële vloeistofsnelheid, L_c de koekdikte en K de permeabiliteit. De gemiddelde specifieke filtratieweerstand is een goede maat voor slib karakteristieken en hangt af van het type slib, type en hoeveelheid flocculant en filtratiedruk. In figuur 4 en 5 zijn typische voorbeelden gegeven van filtratieweerstanden versus dosering flocculant. Vrijwel altijd wordt een minimale filtratieweerstand gevonden. In figuur 6 is een voorbeeld gegeven van een persexperiment. Karakteristiek is de snelle initiële persing gevolgd door een langzame consolidatie. In figuur 7 zijn resultaten van hoge druk persexperimenten te zien. Aan de hand van dit figuur is te zien dat eind droge stof gehaltes van ± 60 gew% mogelijk zijn. Bij deze vochtgehaltes neemt de bindingsenthalpie (maat voor de strekte van de slib-water binding) sterk toe (Herwijn, 1993). Dit betekent dat extreem hoge mechanische krachten nodig zijn om dit gedeelte van het water ter verwijderen. Bij deze vochtgehaltes kan slib beter worden gedroogd.



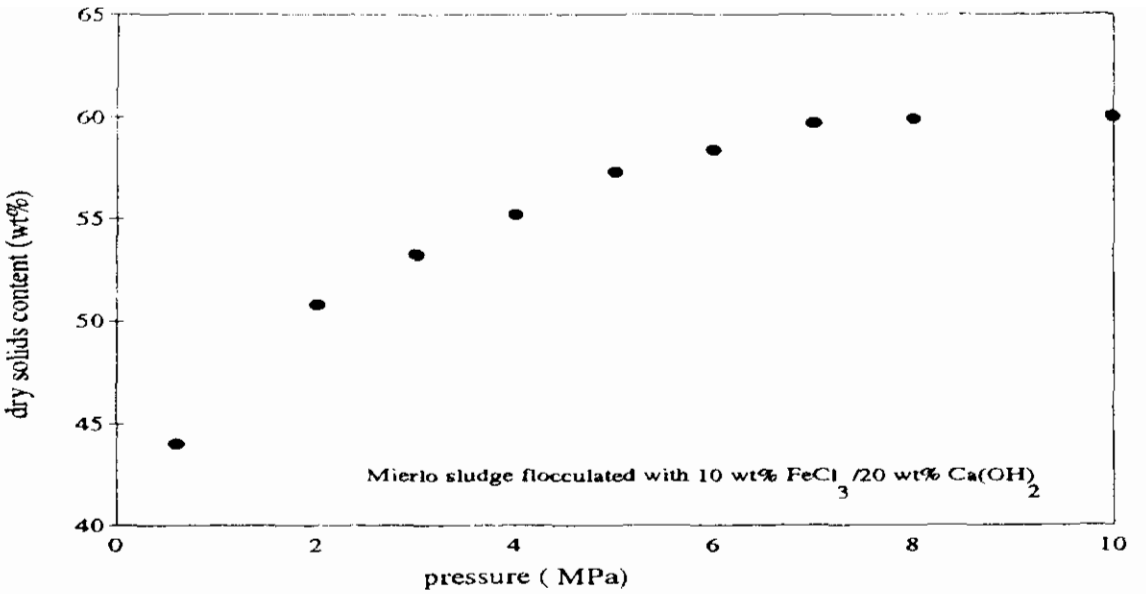
Figuur 4. *Gemiddelde specifieke filtratieweerstand versus concentratie ijzerchloride (concentratie $Ca(OH)_2$ constant op 20 gew%). Doseringen op basis van droge stof gehalte.*



Figuur 5. *Gemiddelde specifieke filtratieweerstand versus concentratie polyelectrolyt. Doseringen op basis van droge stof gehalte.*



Figuur 6. *Voorbeeld van een persexperiment.*



***Figuur** 7. Eind droge stof gehalte versus mechanische druk. Mierlo slib geflocculeerd met 10 gew% $FeCl_3$ en 20 gew% $Ca(OH)_2$ op droge stof basis.*

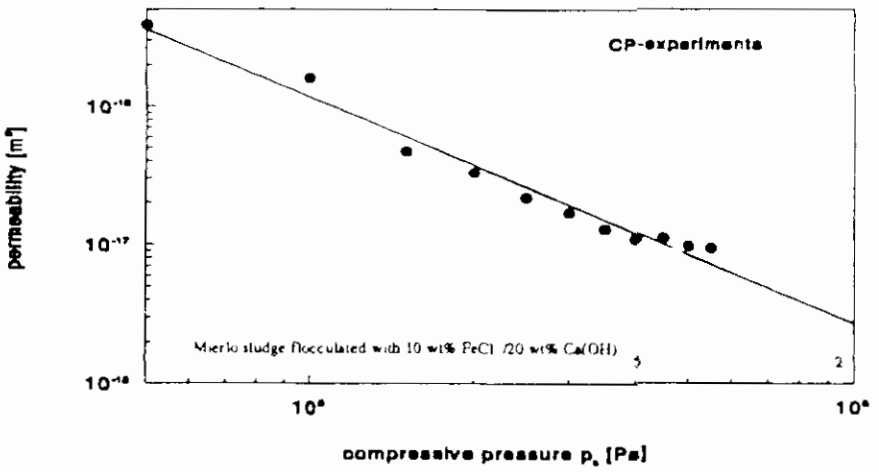
Permeabiliteit en porositeit in relatie tot de compressie druk

In figuur 8 en 9 zijn resultaten van typische compressie-permeabiliteits experimenten weergegeven. De relaties tussen permeabiliteit, porositeit en compressiedruk kunnen in de meeste gevallen worden gefit aan machtsfuncties (van Veldhuizen, 1991). Relaties, die kunnen worden gebruikt zijn (Tiller et al., 1987):

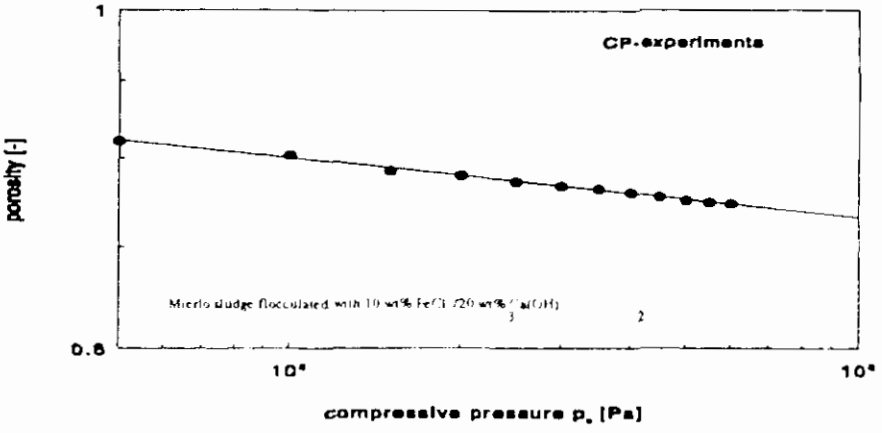
$$\phi_\infty = \phi_o\left(1+\frac{p_s}{p_a}\right)^{-\lambda} \qquad (2)$$

$$K_\infty = K_o\left(1+\frac{p_s}{p_a}\right)^{-\delta} \qquad (3)$$

waarbij ϕ_O en K_O de porositeit en permeabiliteit zijn bij compressie druk p_S=0; λ en δ zijn compressiecoefficienten en p_a is een arbitraire constante. De index oneindig geeft aan dat deze waarden zijn gemeten zijn in evenwichtssituaties. Compressie-permeabiliteits experimenten zijn ook erg bruikbaar voor de karakterisering van slib. Het geeft snel een idee van het eind droge stof gehalte bij verschillende aangelegde mechanische drukken.



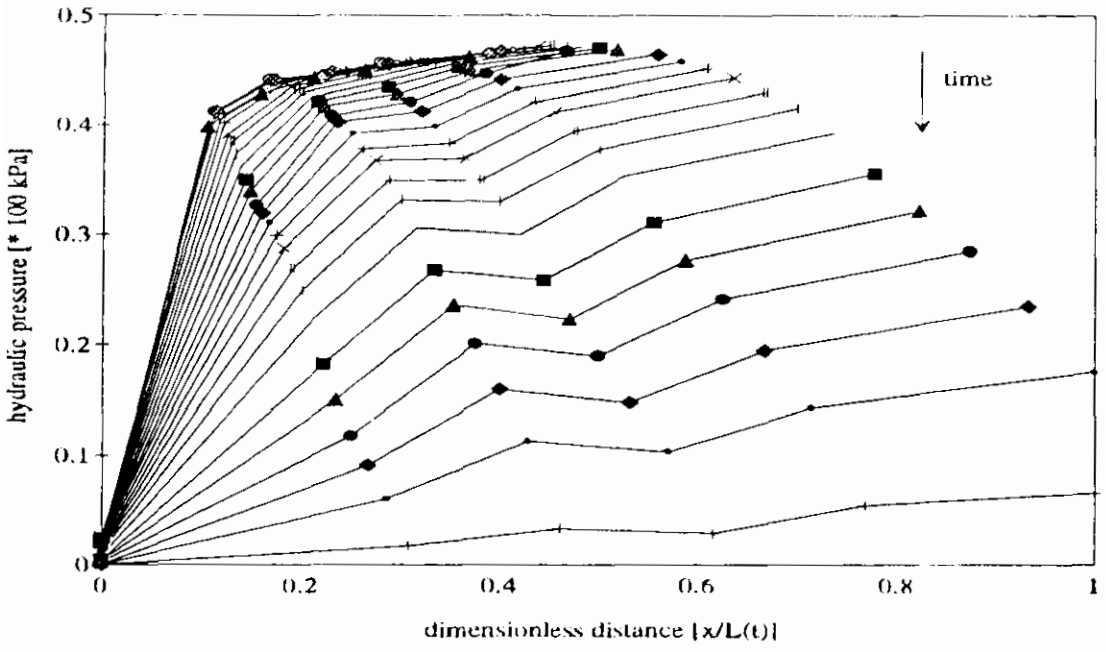
Figuur 8. Voorbeeld van een CP-cel experiment. Permeabiliteit versus compressiedruk.



Figuur 9. Voorbeeld van een CP-cel experiment. Porositeit versus compressiedruk.

Drukverdelingen in slib filterkoeken

In figuur 10 is de vloeistofdrukverdeling tijdens de persfase van slib filterkoek weergegeven. Het eerste profiel is min of meer het einde van de filtratie fase (exacte overgang is moeilijk te bepalen) en het is duidelijk dat er nauwelijks een druk gradiënt aanwezig is in de koek. Dit is typisch voor zeer compressibele filterkoeken zoals die van slib. Aan het einde van de persfase is de vloeistofdruk overal in de koek ongeveer gelijk aan nul, hetgeen een uniforme koekstructuur betekent.



Figuur 10. *Vloeistofdruk profielen als functie van de tijd in een slibfilterkoek tijdens de persfase.*

Modellering van het filtratie en persgedrag

Om de filtratie en persfase van slib te modelleren zijn een aantal basis vergelijkingen noodzakelijk. Dit is een stromingsvergelijking, een krachtenbalans, constitutieve vergelijkingen en continuiteitsvergelijkingen. Voor de stromingsvergelijking wordt de Darcy-Shirato vergelijking gebruikt:

$$v_l - v_s = \frac{1}{\phi}\frac{K}{\eta}\frac{\partial p_l}{\partial x} \tag{4}$$

waarbij v_l en v_S respectievelijk de lineaire vloeistofsnelheid en vaste stof snelheid zijn. Een eenvoudige krachtenbalans leidt tot:

$$\frac{\partial p_l}{\partial x} + \frac{\partial p_s}{\partial x} + (\rho_s(1-\phi) + \rho_l\phi)g = 0 \tag{5}$$

De continuiteitsvergelijking is gelijk aan:

$$\left(\frac{\partial \phi}{\partial t}\right)_x = \left(\frac{\partial q_l}{\partial x}\right)_t \tag{6}$$

Combinatie van bovenstaande vergelijkingen levert een differentiaalvergelijking op, die de verandering van de porositeit in plaats en tijd beschrijft:

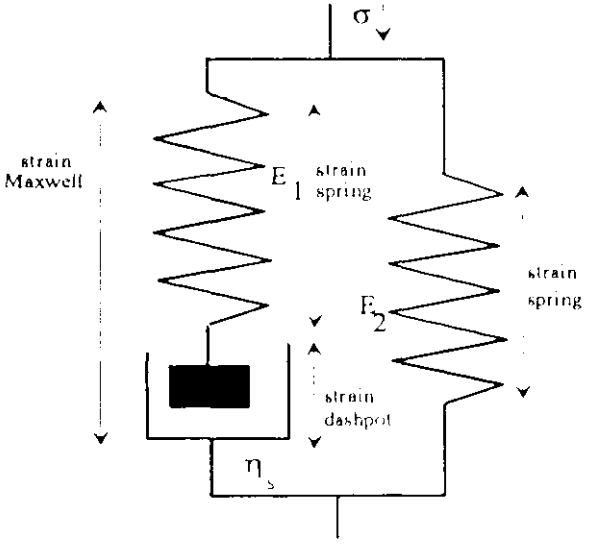
$$\left(\frac{\partial \phi}{\partial t}\right)_x = q_{lm}\left(\frac{\partial \phi}{\partial x}\right)_t + \frac{\partial}{\partial x}\left(\frac{K}{\eta}(1-\phi)\left[(\rho_s-\rho_l)(1-\phi)g + \left(\frac{\partial p_s}{\partial x}\right)_t\right]\right) \tag{7}$$

waarbij q_{lm} de superficiële vloeistof snelheid is door het filter medium. Afhankelijk van de juiste randvoorwaarden kan de filtratie fase of de pers fase worden gemodelleerd (La Heij et al., 1992), mits een constitutieve vergelijking bekend is.
Constitutieve vergelijkingen beschrijven de deformatie van de vaste stof matrix in een filter koek en kunnen alleen experimenteel worden bepaald. De CP-cel is b.v. een apparaat waarmee constitutieve vergelijkingen kunnen worden bepaald. Indien de relaties bepaald m.b.v. de CP-cel worden gebruikt voor de modellering wordt aangenomen dat de koek zich elastisch gedraagt. Dit betekent instantane verandering van de vaste stof matrix bij verandering van de compressie druk. Bovendien verandert de elasticiteitsmodulus van het materiaal met veranderende porositeit; dit betekent niet-lineair elastisch materiaalgedrag. Indien het enige tijd duurt voordat het materiaal deformeert, gedraagt het materiaal zich visco-elastisch. In figuur 11 is een schematische weergave getoond van een standaard vaste stof model. In evenwichtssituatie rust alle druk op de veer E_1 en daarom kan dezelfde waarde van E_1 voor puur elastisch materiaal worden gebruikt. De differentiaalvergelijking, die de rek ε als functie van de tijd beschrijft, is als volgt:

$$\frac{\partial \varepsilon}{\partial t} = -\frac{E_1 \varepsilon}{\Psi} - \frac{\eta_s \frac{\partial p_s}{\partial t}}{\left(\Psi\left(E_2 + \varepsilon \frac{\partial E_2}{\partial \epsilon}\right)\right)} - \frac{p_s}{\Psi}$$

$$\Psi = \left(\eta_s + \frac{E_1}{\left(\frac{1}{\tau} + \frac{\varepsilon}{\eta_s}\frac{\partial E_2}{\partial \varepsilon}\right)} + \frac{\varepsilon \frac{\partial E_1}{\partial \varepsilon}}{\left(\frac{1}{\tau} + \frac{\varepsilon}{\eta_s}\frac{\partial E_2}{\partial \varepsilon}\right)} \right)$$

(8)



standaard lineaire vaste stof model

Figuur 11. Schematische weergave van het standaard vaste stof model.

waarbij τ ($=E_2/\eta_S$) de relaxatietijd is. De relaxatietijd bepaalt de vervormingssnelheid van de vaste stof matrix. De rek is als volgt gerelateerd aan de porositeit:

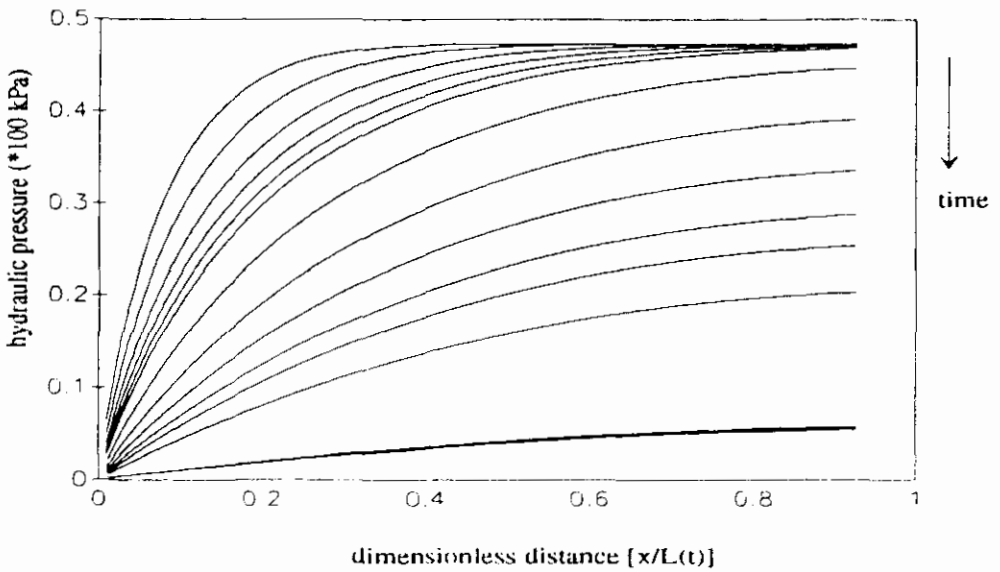
$$\varepsilon = \frac{(1-\phi_o)}{(1-\phi)} - 1 \qquad (9)$$

Vergelijkingen (7) en (8) moeten gekoppeld worden opgelost om lokaal en op elke tijdstap de verandering van de porositeit in de filterkoek te berekenen.

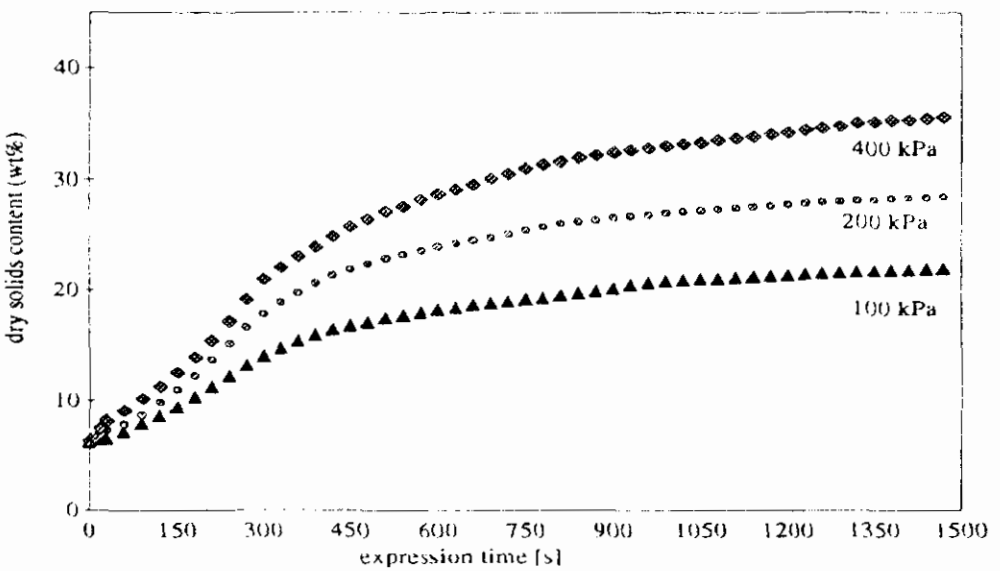
Modellerings resultaten

Omdat de porositeit als functie van plaats en tijd kan worden berekend, kan ook de compressie en de vloeistofdruk als functie van plaats en tijd worden berekend. In figuur 12 zijn berekende vloeistofdruk profielen versus

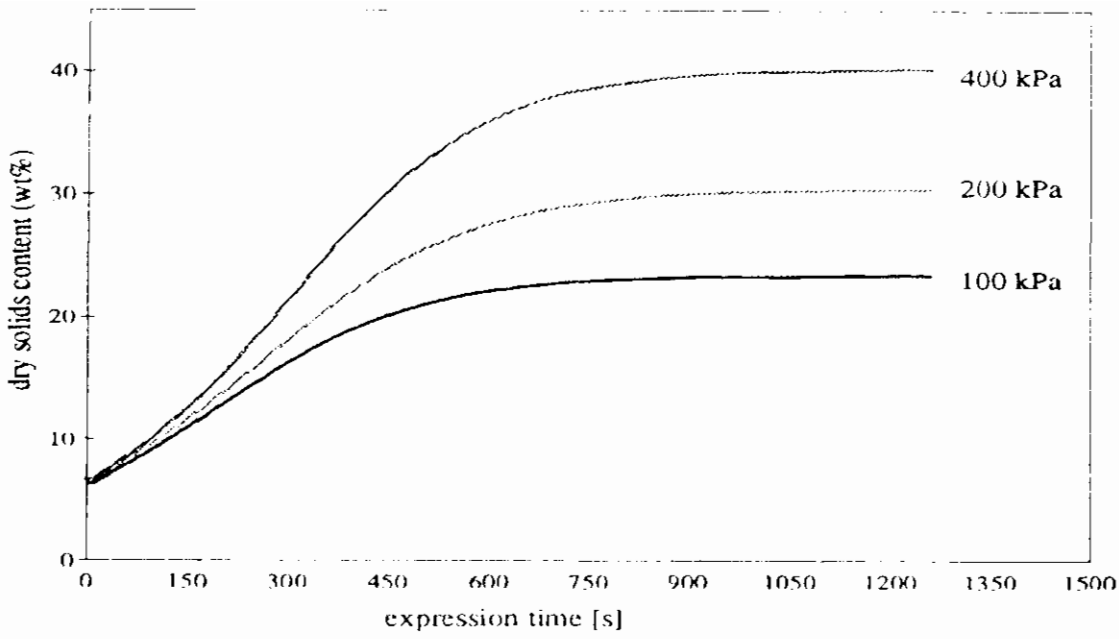
dimensieloze afstand als functie van de tijd uitgezet. De berekeningen zijn uitgevoerd op basis van niet-lineair elastisch materiaalgedrag. De overeenkomst tussen model en experiment is acceptabel. In figuur 13a is de hoeveelheid droge stof versus perstijd voor slib geflocculeerd met $FeCl_3/Ca(OH)_2$ volgens experiment uitgezet. In figuur 13b zijn de modelberekeningen op basis van niet-lineair elastisch materiaalgedrag uitgezet. Wederom is een acceptabele overeenkomst te zien tussen model en experiment. Volgens de modelberekeningen wordt de evenwichtssituatie iets eerder bereikt dan volgens de experimenten. Dit wordt waarschijnlijk veroorzaakt doordat er enige kruip (visco-elastisch materiaalgedrag) aan het einde van de persfase optreedt. Bovendien is te zien aan de hand van figuur 13a dat de evenwichtssituatie ongeacht de aangelegde druk altijd op hetzelfde tijdstap wordt bereikt. In figuur 14 is een experimenten en model berekening getoond voor slib geflocculeerd met polyelectrolyt. Omdat het materiaal langzaam deformeert, moet worden aangenomen dat het materiaal zich visco-elastisch gedraagt. Er is een goede overeenkomst tussen model en experiment.



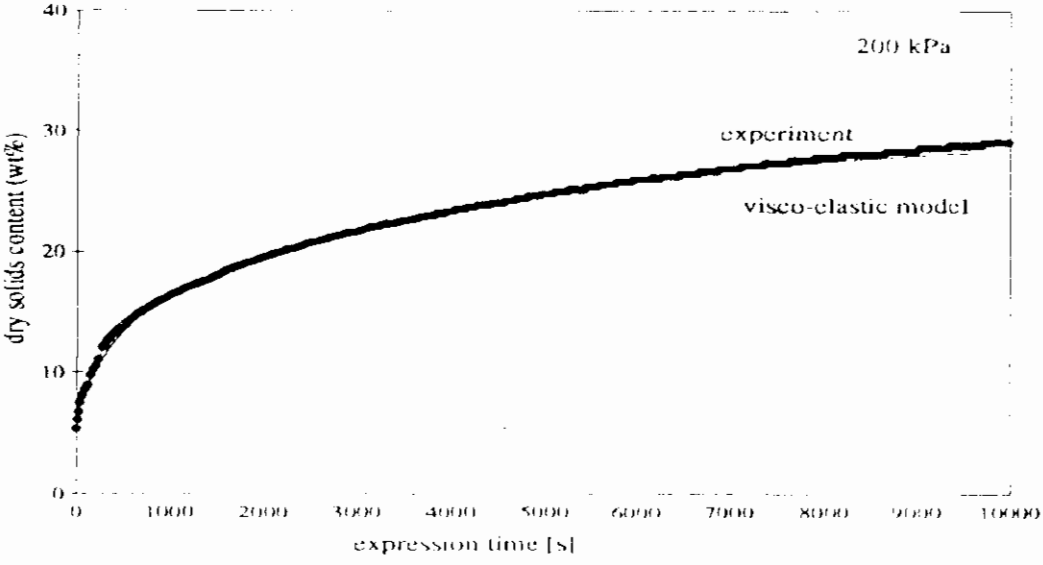
Figuur 12. *Berekende vloeistofdruk profielen als functie van de tijd.*



Figuur 13a. *Gemiddelde hoeveelheid vaste stof versus tijd voor de persfase volgens experiment. Mierlo slib geflocculeerd met 10 gew% $FeCl_3$ en 20 gew% $Ca(OH)_2$ op d.s. basis.*



Figuur 13b. *Gemiddelde hoeveelheid vaste stof versus tijd voor de persfase volgens model. Mierlo slib geflocculeerd met 10 gew% $FeCl_3$ en 20 gew% $Ca(OH)_2$ op d.s. basis.*



Figuur 14. *Gemiddelde hoeveelheid vaste stof versus tijd voor de persfase volgens experiment en model. Mierlo slib geflocculeerd met 1.5 gew% p.e..*

Conclusies

Met behulp van de hierboven besproken modellen kan het ontwateringsgedrag van slib acceptabel worden beschreven. Het materiaalgedrag kan elastisch of visco-elastisch zijn. Deze fundamentele modellen kunnen worden beschouwd als een goede basis voor apparaatmodellen, waarmee optimalisatie van ontwerp en operatie kunnen worden uitgevoerd.
De snelste ontwatering vindt altijd plaats bij optimale flocculatiecondities. Karakteristiek voor de persing van zuiveringsslibben is de snelle initiële persing, gevolgd door een langzame consolidatie. De tijd waarop de evenwichtssituatie wordt bereikt is onafhankelijk van de aangelegde mechanische druk. Bij lage drukken (300-400 kPa) kunnen reeds hoge droge stof gehaltes (35-40 gew%) worden

bereikt. Echter bij hoge drukken (6-10 MPa) kunnen droge stof gehaltes van ± 60 gew% worden bereikt.

Symbolenlijst

E_1	elasticiteitsmodulus	Pa
E_2	elasticiteitsmodulus	Pa
g	zwaartekrachtversnelling	m s^{-2}
K	permeabiliteit	m^2
K_0	permeabiliteit bij p_s=0	m^2
L_c	koekdikte	m
p	aangelegde filtratie-pers druk	Pa
p_a	constante in vergelijkingen 2 en 3	Pa
p_s	compressie druk	Pa
R_c	koekweerstand	m^{-1}
t	tijd	s
v_l	lineaire vloeistof snelheid	m s^{-1}
v_s	lineaire vaste stof snelheid	m s^{-1}
w	hoeveelheid vaste stof per opp. eenheid	kg m^{-2}
q_l	superficiële vloeistofsnelheid	m s^{-1}
q_{lm}	superficiële vloeistofsnelheid door filtermedium	m s^{-1}
x	afstand in filterkoek	m

Griekse symbolen

α	specifieke filtratieweerstand	m kg^{-1}
ε	rek	-
ϕ	porositeit	-
ϕo	porositeit bij p_s=0	-
η	vloeistof viscositeit	Pa s
η_s	viscositeit standaard vaste stof model	Pa s
ρ_l	dichtheid vloeistof	kg m^{-3}
ρ_s	dichtheid vaste stof	kg m^{-3}
σ	spanning	Pa
τ	relaxatietijd	s

Literatuur

Herwijn, A.J.M., Coumans, W.J.
Characterization of sewage sludges, fundamentals and results
Workshop sewage sludge the Netherlands-Japan, 17-23 oktober 1993, Miyazaki, Japan.

La Heij, E.J., Herwijn, A.J.M., Coumans, W.J., Kerkhof, P.J.A.M.
Filtration and expression behaviour of sewage sludge
gepresenteerd op het jaarlijkse AIChE congres, november 1992, Miami Beach.

Shirato, M., Sambuichi, M., Kato, H., Aragaki, T.
Internal flow mechanism in filter cakes
A.I.Ch.E. J., vol. 15, no.3, p.p. 405-409, 1969.

Tiller, F.M., Yeh, C.S.
The role of porosity in filtration. Part XI: filtration followed by expression

A.I.Ch.E. J., vol. 33, no.8, p.p. 1241-1257, 1987.

Veldhuizen, A.J.W. van
Compressiegedrag van zuiveringsslib
Afstudeerverslag, oktober 1991.

PUBLIKATIEREEKS "TOEKOMSTIGE GENERATIE RIOOLWATERZUIVERINGSINRICHTINGEN RWZI 2000" [1]

1 "Behandeling van stedelijk afvalwater in de toekomst"
Een haalbaarheidsonderzoek. I. Eindrapport II. Werkrapport
RIZA, TNO-Maatschappelijke Technologie en Witteveen & Bos Raadgevende ingenieurs
Juli 1986

2 "Toekomstige generatie rioolwaterzuiveringsinrichtingen; RWZI 2000"
Onderzoekplan
RIZA, STORA
Januari 1988

3 "Jaarverslag 1988"
RIZA, STORA
Maart 1989

4 "Slibontwatering; een voorstudie"
TU-Delft, TU-Eindhoven
RWZI 2000 89-01
Januari 1989

5 "Knelpunten bij de invoering van defosfatering"
Witteveen & Bos Raadgevende ingenieurs
RWZI 2000 89-02
April 1989

6 "Selectieve verwijdering van zware metalen uit ruw rioolwater met behulp van een magneetsysteem"
Smit-Nymegen, TNO-Maatschappelijke Technologie
RWZI 2000 89-03
Oktober 1989

7 "Verwijdering van zware metalen uit zuiveringsslib door elektrolyse"
TNO-Maatschappelijke Technologie
RWZI 2000 89-04
Oktober 1989

---

[1] Te bestellen bij:
STOWA, Postbus 8090, 3503 RB Utrecht
tel. 030-321199

8 "Hydrolyse van zuiveringsslib in combinatie met anaërobe vergisting"
TNO-Maatschappelijke Technologie
RWZI 2000 89-05
Oktober 1989

9 "Het drogen van zuiveringsslib met het Carver-Greenfieldproces"
TNO-Maatschappelijke Technologie, Witteveen & Bos Raadgevende ingenieurs
RWZI 2000 89-06
December 1989

10 "Natte oxydatie van zuiveringsslib met het Vertech-systeem"
TNO-Maatschappelijke Technologie, Witteveen & Bos Raadgevende ingenieurs
RWZI 2000 89-07
December 1989

11 "Symposium "RWZI 2000" d.d. 5 oktober 1989"
RIZA, STORA
RWZI 2000 89-08
December 1989

12 "Jaarverslag 1989"
RIZA, STORA
RWZI 2000 90-01
Maart 1990

13 "AB-Systemen; een inventarisatie"
DHV Raadgevend Ingenieursbureau BV
RWZI 2000 90-02
September 1990

14 "Vergisting van aëroob gestabiliseerd slib"
DHV Raadgevend Ingenieursbureau BV
RWZI 2000 90-03
Augustus 1990

15 "Het afleiden van procestechnologische relaties uit bedrijfsgegevens van rwzi's"
DHV Raadgevend Ingenieursbureau BV
RWZI 2000 90-04
December 1990

16 "Automatische regeling van het slibgehalte in beluchtingstanks"
Adviesbureau BKH
RWZI 2000 90-05
September 1990

17 "Verkenning Bio-Denitro/Bio-Denipho"
Witteveen & Bos Raadgevende ingenieurs
RWZI 2000 90-06
Juni 1990

18 "Linpor-sponsjes als dragermateriaal bij de aërobe zuivering van rioolwater"
TNO-Maatschappelijke Technologie
RWZI 2000 90-07
Oktober 1990

19 "Jaarverslag 1990"
RIZA, STORA
RWZI 2000 91-01
Maart 1991

20 "Deep Shaft-systemen; een inventarisatie"
DHV Raadgevend Ingenieursbureau BV
RWZI 2000 91-02
Maart 1991

21 "Perspectives for the utilization of membrane-assisted sludge retention in municipal waste water treatment plants"
A feasibility study
RU-Groningen
RWZI 2000 91-03
Juni 1991

22 "Jaarverslag 1991"
RIZA, STOWA
RWZI 2000 92-01
Maart 1992

23 "Vergisten van zuiveringsslib; een vergelijking tussen thermofiele en mesofiele slibgisting"
Haskoning B.V., RIZA, LU-Wageningen, DHV Water B.V.
RWZI 2000 92-02
Maart 1992

24 "First Dutch-Japanese workshop on the treatment of municipal waste water; 8-11 april 1991, Heelsum, The Netherlands. Part I and part II.
RIZA, STOWA, TU-Delft
RWZI 2000 92-03
Maart 1992

25 "Biologische fosfaatverwijdering in combinatie met een korrelreactor"
LU-Wageningen, DHV Water B.V.
RWZI 2000 92-04
Augustus 1992

26 "Anaërobe behandeling van stedelijk afvalwater in Nederland"
Covernota van het uitgevoerde onderzoek 1976 - 1991
LU-Wageningen, Haskoning B.V.
RWZI 2000 92-05
Mei 1992

27 "Vergaande nutriëntenverwijdering op een zeer laagbelaste aktiefslibinstallatie"
Zuiveringsschap Hollandse Eilanden en Waarden, Grontmij N.V.
RWZI 2000 92-06
Oktober 1992

28 "Ontwikkeling van een slib-op-drager systeem voor de aërobe zuivering van stedelijk afvalwater"
Fase II: Onderzoek naar de processtabiliteit en optimalisatie van het zuiveringsrendement.
TNO-IMW
RWZI 2000 92-07
Oktober 1992

29 "Behandeling van stedelijk afvalwater met het schachtreactorsysteem"
V & P Waste Water Management B.V.
RWZI 2000 92-08
Juli 1994

30 "Stikstofverwijdering uit interne stromen op rwzi's"
DHV Water B.V.
RWZI 2000 92-09
December 1992

31 "Jaarverslag 1992"
RIZA, STOWA
RWZI 2000 93-01
April 1993

32 "Onderzoek demonstratie-installaties magnetische defosfatering"
Envimag B.V.
RWZI 2000 93-02
April 1993

33 "Modelvorming en optimalisatie van biologische defosfatering van afvalwater: Microbiële aspekten"
LU-Wageningen, vakgroep Microbiologie
RWZI 2000 93-03
November 1993

34 "Jaarverslag 1993"
RIZA, STOWA
RWZI 2000 94-01
Juli 1994

35 "Fundamentele aspekten van slibontwatering"
Deel 1: Samenvattend verslag
Deel 2: Flocculatiemechanismen
Deel 3: Filtratie-expressie modellering
Deel 4: Filtratie expressie experimenten
Deel 5: Slib-water binding
Deel 6: Karakterisering van slibben
Deel 7: Ontwikkeling nieuw CST-apparaat
Deel 8: Congresbijdragen
TU-Eindhoven, Laboratorium voor Scheidingstechnologie
RWZI 2000 94-02
Juli 1994