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FUNDAMENTAL ASPECTS OF SLUDGE FILTRATION AND EXPRESSION

E. J. LA HEIJ, P. J. A. M. KERKHOF*, A. J. M. HERWIJN and W. J. COUMANS

Laboratory for Separation Technology, Department of Chemical Engineering, Eindhoven University of Technology, P.O. Box 513, NL-5600 MB, Eindhoven, The Netherlands

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Abstract—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 pressures 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.

Key words—sludge, filtration, expression, flocculants, pressure profiles, porosity, permeability, modelling

NOMENCLATURE

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 equations 3 and 4 (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 (ps = 0) (—)
η = viscosity dash pot (Pa s)
μ = viscosity filtrate (Pa s)
ρ_l = density liquidkg m^{-3}
ρ_s = density solids (kg m^{-1})
τ = relaxation time (s)

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/y. 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 percent of sludge disposal. In the future the use in agriculture will decrease due to more severe limits of allowed heavy metal concentration. 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 (1991) 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".

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 be presented as follows. Taking the present average water content after dewatering at

*Author to whom all correspondence should be addressed.

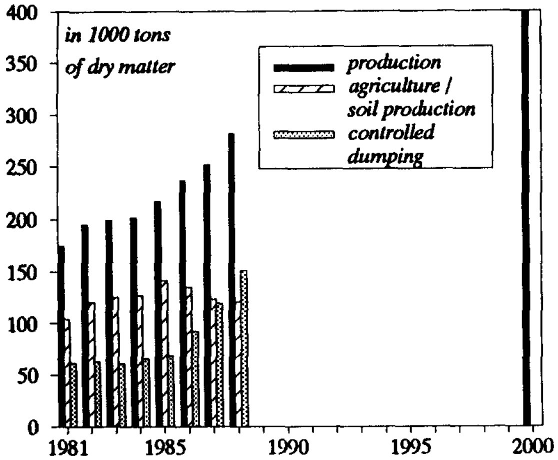

Fig. 1. Production and disposal of sludge in the Netherlands (after data of Werumeus Buning, 1991).

4 kg water/kg ds, we must aim at a reduction in the future to 1.5 kg water/kg ds, corresponding to 40 wt% solids. This would mean that in spite of the expected growth of sludge from 300,000 tons ds/y now to 400,000 tons ds/y. in 2000, we would still have a considerable reduction of 500,000 tons/y. on a total base. This would correspond to a yearly savings of about Dfl. 33,000,00,-, calculated at present costs of Dfl. 660,-/ton for incineration (Werumeus Buning, 1991). 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 80,000,00/y. could be seen as a reasonable target.

2. EXPERIMENTAL

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

2.1. *The filtration-expression cell (FE-cell)*

The cell, as shown in Fig. 2, 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. A non-porous piston is placed on top of the slurry and gas pressure is applied and filtration starts. The filtrate is collected in a beaker on a balance and data are transferred to an on-line computer. After a while expression starts and also the expression rate can be followed. The transition point from filtration to expression can be determined by plotting $dV/d\sqrt{t}$ vs t (V is filtrate volume). At the point where this line starts to bend off begins the expression phase. 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. In order to study the hydraulic pressure distribution in the filter cake, a number of capillaries of different length, which are connected to pressure transducers, can be placed in the filter cell. By using a mixture of clay and glycerol instead of a piston, the sludge can be expressed.

2.2. *The compression–permeability cell (C–P cell)*

In modelling the dynamic flow rate of filtrate and expression the relations between permeability, porosity and compressive pressure are of great importance. The C–P cell with which these relations are determined is shown in Fig. 3. 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 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.

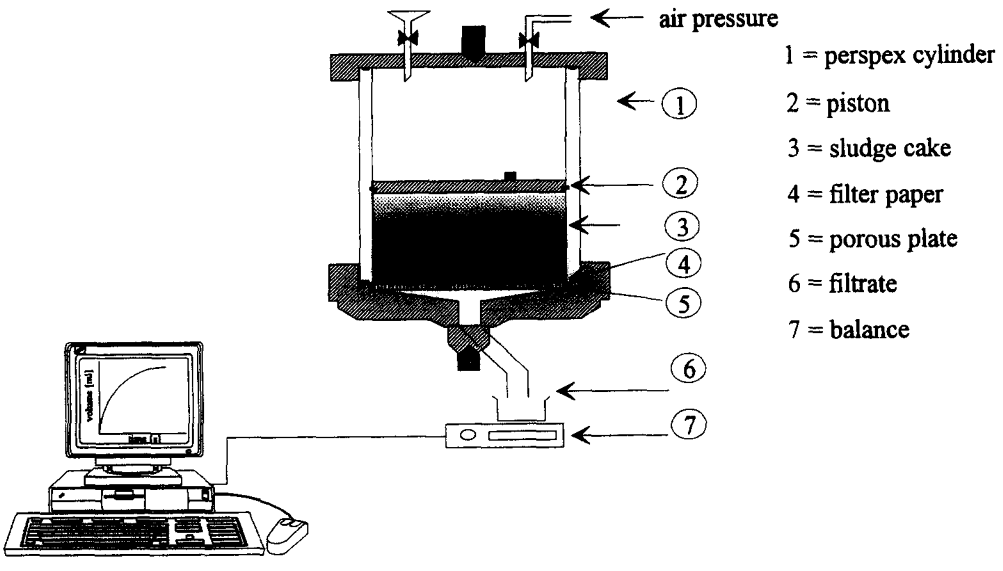

Fig. 2. Diagram of filtration-expression cell.

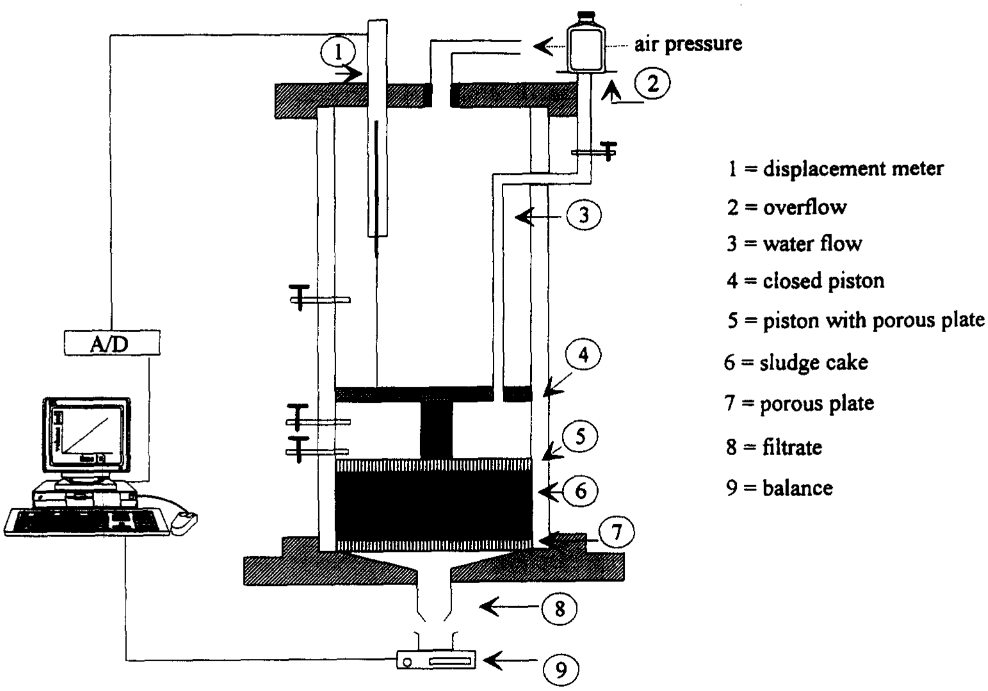

Fig. 3. Diagram of compression–permeability cell.

3. EXPERIMENTAL RESULTS

3.1. Filtration and expression experiments

A first interpretation of filtration curves is to determine the average specific cake resistance α_{av}, as defined by

$$\alpha_{av} = R_c/w \quad (1)$$

$$R_c = \frac{\Delta_{pl}}{\mu u_l} = L_c/K$$

in which R_c is the cake resistance, w is the cake mass per unit area, p_l is the filtration pressure, μ is the liquid velocity, u_l is the superficial liquid velocity, L_c is the cake thickness and K is the permeability.

The average 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. 4, in which α_{av} is plotted vs the dosage of iron chloride. Analogous results have been obtained with addition of polyelectrolytes. In this case a minimum is observed, indicating an optimal dosage of 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.

In Figs 5 and 6 results of expression experiments are shown. It can be seen that dry solids contents of 35–40 wt% already can be reached at pressures of 300–400 kPa and that 60 wt% can be reached at pressure of 10 MPa. The values shown in Fig. 5 and Fig. 6 include flocculant dosage. The dry solids contents are remarkably high in comparison with the dry solids contents reached in practice ($\pm$ 30 wt% at 1.5 MPa in filter presses vs $\pm$ 50 wt% at laboratory scale). To the authors knowledge these high dry solids contents have never been shown in the filtration-expression literature.

3.2. Permeability and porosity in relation to compressive pressure

In Fig. 7 results of typical compression–permeability experiments are shown. Relations between porosity ϵ, permeability K and compressive pressure p_s are found. The values determined with the C–P cell are measured in an equilibrium (steady-state) situation and are only representative for the final equilibrium situations (no deformation of the filter

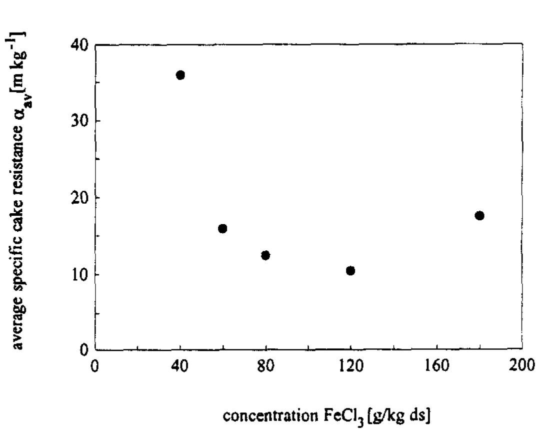

Fig. 4. Effect of flocculant dosage on the average specific cake resistance α_{av} for Mierlo sludge flocculated with iron chloride and lime at $\Delta P = 0.5$ bar.

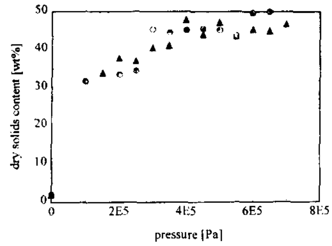

Fig. 5. Dry solids content versus applied expression pressure for Mierlo sludge flocculated with iron chloride (●) and polyelectrolytes (▲).

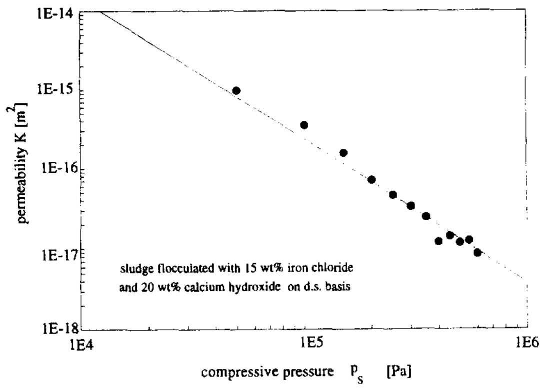

Fig. 7. An example of a C–P experiment. Permeability K_∞ vs compressive pressure p_s.

cake anymore). The relation between permeability and porosity can be written as

$$K = K_o\left(\frac{\epsilon}{\epsilon_o}\right)^{\delta/\lambda} \tag{2}$$

The equilibrium values of the porosity ϵ_∞ and permeability K_∞ can be related to the compressive pressure by power law functions (van Veldhuizen (1991); Tiller and Yeh (1987))

$$\epsilon_\infty = \epsilon_o\left(1 + \frac{p_s}{p_a}\right)^{-\lambda} \tag{3}$$

$$K_\infty = K_o\left(1 + \frac{p_s}{p_a}\right)^{-\delta} \tag{4}$$

where ϵ_o and K_o 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 characterization of different sludges. They quickly give an idea of the compressibility of the sludges and therefore about the dry solids contents t different applied expression pressures.

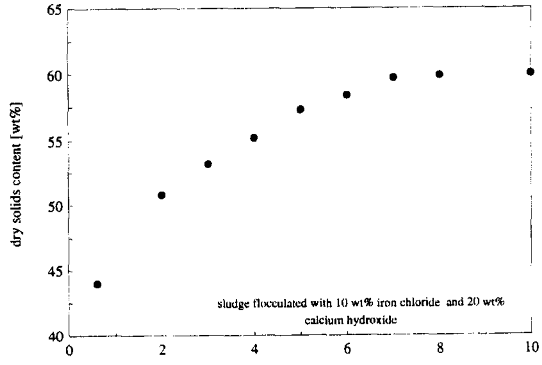

Fig. 6. Dry solids content versus applied expression pressure for Mierlo sludge for the high pressure range. Sludge flocculated with iron chloride.

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.*, 1969) is used which takes into account the solids movement

$$v_l - v_s = \frac{1}{\epsilon}\frac{K}{\mu}\frac{\partial p_l}{\partial_x} \tag{5}$$

where v_l and v_s are the linear liquid and solids velocity respectively. The linear liquid velocity times the porosity gives the superficial liquid velocity ($v_l = q_l$). A simplified force balance leads to the following equation

$$\frac{\partial p_l}{\partial x} + \frac{\partial p_s}{\partial x} + (\rho_l\epsilon + \rho_s(1-\epsilon))\mathbf{g} = 0 \tag{6}$$

The continuity equation reads

$$\left(\frac{\partial \epsilon}{\partial t}\right)_x = \left(\frac{\partial \epsilon}{\partial x}\right)_t \tag{7}$$

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

$$\left(\frac{\partial \epsilon}{\partial t}\right)_x = u_{lm}\left(\frac{\partial \epsilon}{\partial x}\right)_t + \frac{\partial}{\partial x}\left[\frac{K}{\mu}(1-\epsilon) \times\left((\rho_s - \rho_l)(1-\epsilon)\mathbf{g} - \left(\left(\frac{\partial p_s}{\partial x}\right)_t\right)\right)\right] \tag{8}$$

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 $\mathbf{g}$ the gravity acceleration.

Depending on the boundary conditions the filtration and expression phase can be modelled (La Heij *et al.*, 1992). The initial condition for the filtration phase is that the porosity equals the unstressed porosity ϵ_0 throughout the whole cake. The initial condition for the expression phase is determined by the end of the filtration phase. The time at which the expression phase starts can be determined experimentally as described in Section 3.1. The initial porosity profile is the calculated profile at the end of the filtration phase. For the permeability equation (2) can be used. The change of the porosity with changing compressive pressure for dynamically modelling can then be determined by the power function of equation 3 if the material behaves elastic or by a visco-elastic rheological model if the material behaves visco-elastic (see Section 4.2). Therefore, 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 C–P cell (discussed in Sections 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 C–P 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. 8. The elastic modulus increases with decreasing porosity. Although there is much criticism on the C–P cell (Willis *et al.*, 1974; Wakeman, 1978), there is still now good alternative for the cell and it still gives an acceptable analysis of filtration-expression data, which will be shown later in this article.

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. 8 a three parameter model is shown. The differential equation describing the strain as a function of time can be written as [if E_2 is only a function of the strain, La Heij (1994)]

$$\left(\frac{\partial \epsilon}{\partial t}\right) = -\frac{p_s + E_1\epsilon + \tau\dfrac{\partial p_s}{\partial t}}{\left(\tau(E_1 + E_2) + \tau\epsilon\dfrac{\partial E_1}{\partial \epsilon}\right)} \tag{9}$$

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

$$\epsilon = \frac{(1-\epsilon_o)}{(1-\epsilon)} - 1 \tag{10}$$

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 [E_1 can be calculated by use of equation (3) and equation (10)]. Because the material deformation and the liquid flow through the cake occur simultaneously, the relaxation time τ (and thus E_2 and η) can only be determined directly from a filtration or expression experiment.

Equations (7) and (8) must be solved simultaneously to calculate locally and at every time the change of the porosity in the filter cake. To the authors knowledge, in the filtration-expression literature the way of solution as presented here has not been undertaken so far.

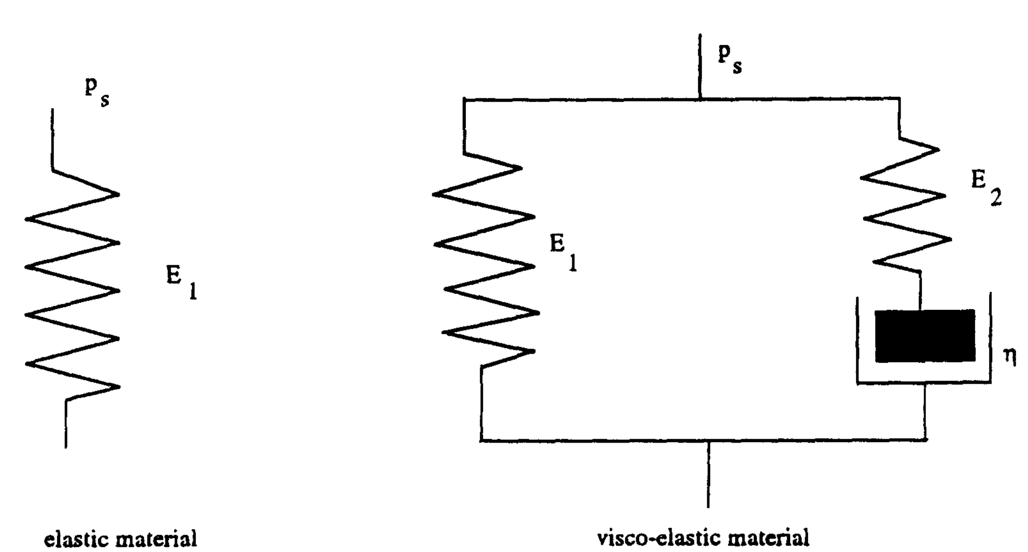

Fig. 8. Different models for material behaviour.

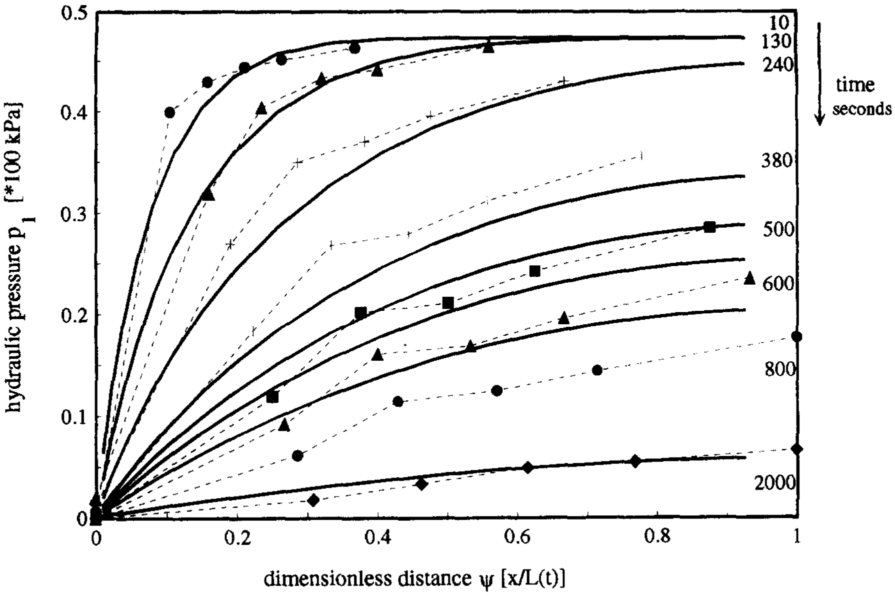

Fig. 9. Hydraulic pressure distribution during the expression phase in a filter cake according to experiment and model. Sludge from rwzi Eindhoven flocculated with 10 wt% $FeCl_3$ and 40 wt% $Ca(OH)_2$ on dry solids base.

4.3. *Modelling results*

Since 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. 9 calculated and measured hydraulic pressure profiles for the expression phase based on non-linear elastic material behaviour are shown. As can be seen, there is an acceptable agreement between model and experiment.

In Fig. 10 the measured and calculated average dry solids content vs time for different expression pressures 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. 10 that the final equilibrium situation is reached at the same time regardless of the applied expression pressure. Finally it can be seen from Fig. 10 that already at 400 kPa dry solids contents of about 38 wt% can be reached. In Fig. 11 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. Although there is some uncertainty in the determination of the C–P cell parameters, which can also cause some difference between model and experiment, it was not possible to describe the slow consolidation at the end of this experiment on the basis of elastic material behaviour. In Fig. 12 the expression time vs cake thickness according to experiment and model is shown. Again there is an

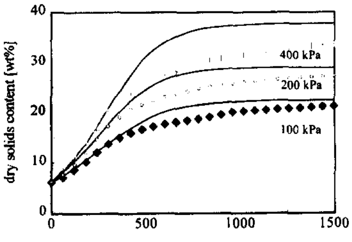

Fig. 10. Average dry solids content vs time according to experiment (symbols) and calculations (solid lines). Mierlo sludge flocculated with 15 wt% $FeCl_3$ and 20 wt% $Ca(OH)_2$ on dry solids base.

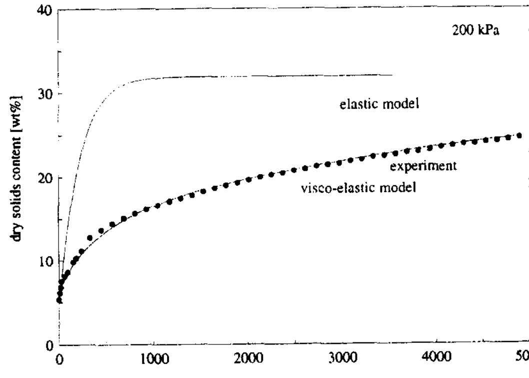

Fig. 11. Average dry solids content versus expression time; experiment and model (elastic and visco-elastic behaviour). Mierlo sludge flocculated with 1.5 wt% polyelectrolyte.

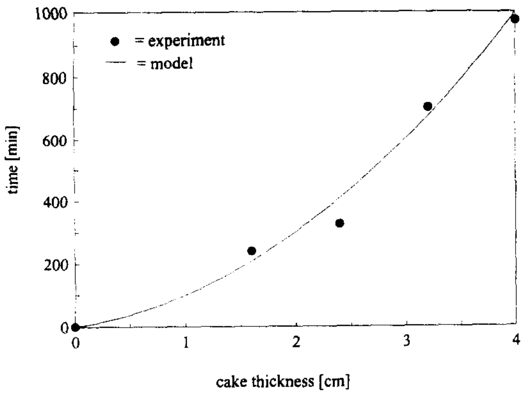

Fig. 12. Expression time vs cake thickness according to experiment and model. Mierlo sludge flocculated with 1.5 wt% polyelectrolyte.

acceptable agreement between model and experiment. The dewatering time increases with the square of the cake thickness (see also equation 8).

5. CONCLUSIONS

With the above discussed models the dewatering behaviour of sewage sludges can be acceptable predicted. 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). Characteristics for the expression of sewage sludges is the rapid initial expression followed by 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 pressures 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.

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