# Filtration and expression of sewage sludge

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# FILTRATION AND EXPRESSION OF SEWAGE SLUDGE

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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

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

$$\varepsilon = \varepsilon_0(1 + p_s/p_a)^{-\lambda} \qquad (1)$$

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

where

$\varepsilon$ = local porosity, [-]
$K$ = local permeability, $[m^2]$
$p_s$ = compressive pressure, [Pa]
$p_a$ = constant, [Pa]
$\lambda, \delta$ = compressibility coefficients, [-]

$\varepsilon_0$ 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 d place in a filter cake:

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

$t$ = time, [s]
$\eta$ = viscosity filtrate, [Pa s]
$\rho_s$ = density solids, $[kg\ m^{-3}]$
$\rho_l$ = 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 $\omega$:

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

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

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

with initial condition for filtration:

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

boundary conditions for filtration:

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

$$u_{1m} = \frac{K_m}{\Delta x_m \eta}(p - p_{s,\omega=0}) \qquad \text{at } \omega = \omega_0 \quad t>0 \qquad (8)$$

where

$K_m$ = permeability filtermedium, $[m^2]$
$\Delta x$ = 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:

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

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

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 $\varepsilon$ 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.

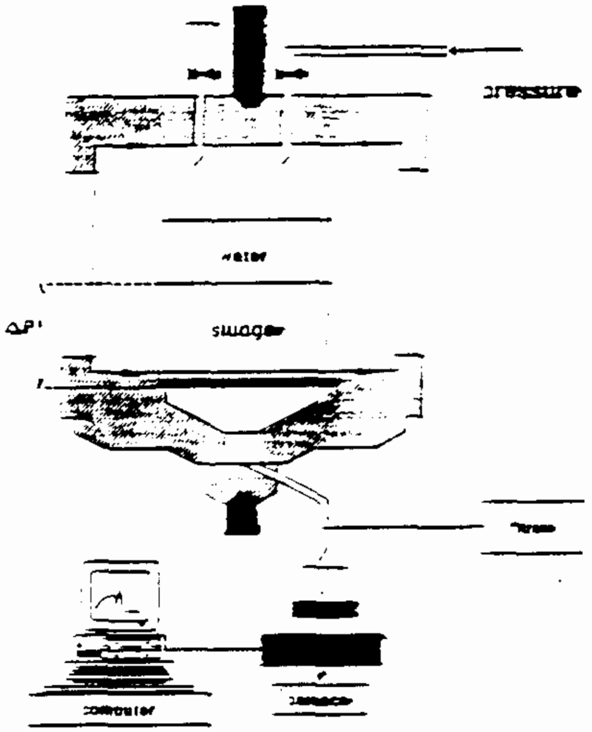

*Figure 1. Schematic diagram of filtration/drainage/expression device.*

## 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 $\varepsilon$ 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.

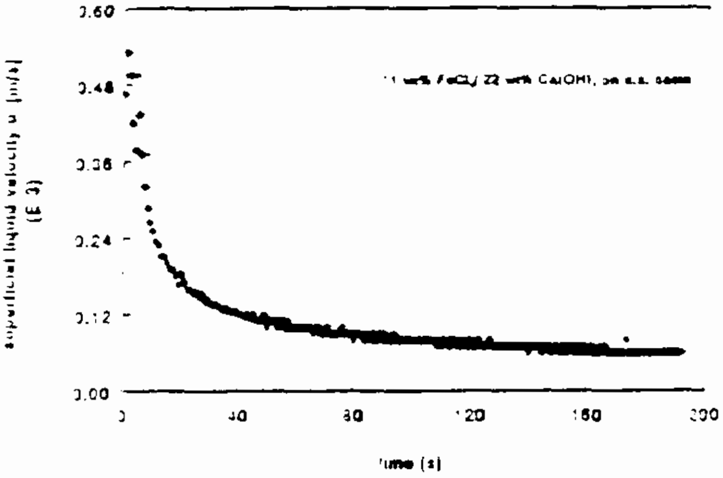

*Figure 2. Superficial liquid velocity $u_{lm}$ versus time, drainage experiment (sludge flocculated with 11 wt% $FeCl_3$ and 20 wt% $Ca(OH)_2$ on dry solids basis; $\Delta p$=40 kPa).*

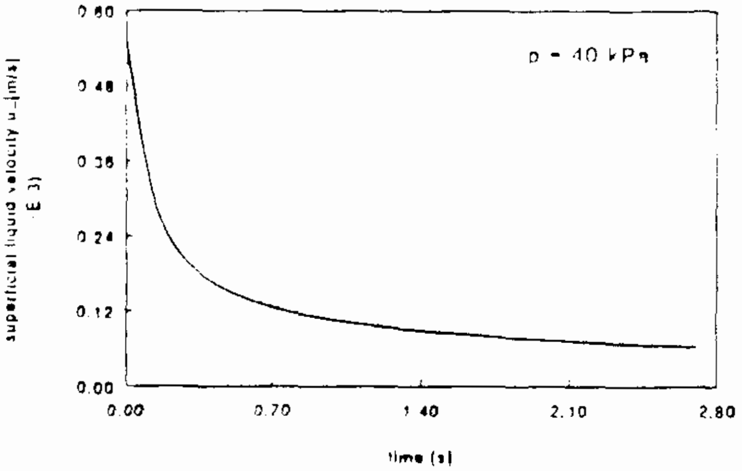

*Figure 3. Calculated superficial liquid velocity versus time; elastic material properties.*

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.

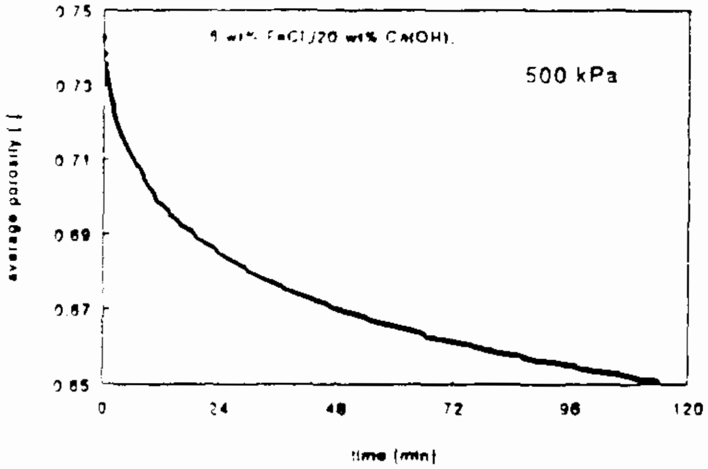

*Figure 4. Average porosity versus time, expression experiment (sludge flocculated with 6 wt% $FeCl_3$ and 20 wt% $Ca(OH)_2$ on dry solids basis; $\Delta p$=500 kPa).*

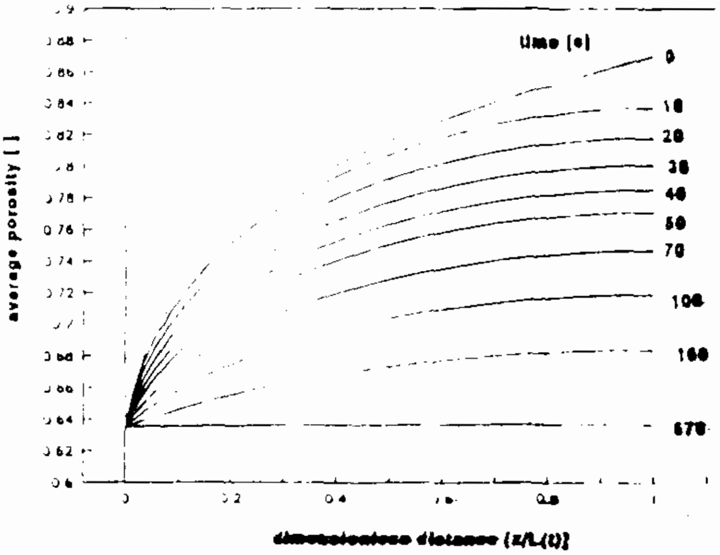

*Figure 5. Calculated porosity profiles during expression phase; $\Delta P$=500 kPa.*

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 $\eta_s$ 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 $\eta_s$. 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 $\alpha_{av}$ [m/kg] is shown. This $\alpha_{av}$ 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 $\alpha_{av}$. Therefore the measured $\alpha_{av}$ during a filtration experiment is often a sum of liquid flow resistance and visco-elasticity/plasticity.

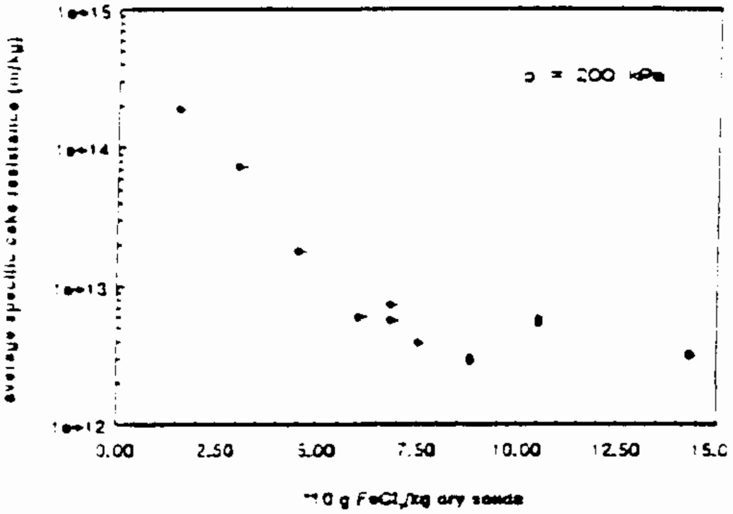

*Figure 6. Specific cake resistance $\alpha_{av}$ versus dosage $FeCl_3$ (on dry solids basis).*

## 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

| | | |
|---|---|---|
| | void ratio | [-] |
| | elastic modulus | [Pa] |
| | gravity acceleration | [m $s^{-2}$] |
| | permeability | [$m^2$] |
| $_0$ | permeability at $p_s$=0 | [$m^2$] |
| $_m$ | medium permeability | [$m^2$] |
| | applied filtration or expression pressure | [Pa] |
| $_h$ | hydraulic pressure | [Pa] |
| $_s$ | compressive pressure | [Pa] |
| $_{s,\omega=0}$ | compressive pressure at $\omega$=0 | [Pa] |
| $_a$ | constant | [Pa] |
| | time | [s] |
| $_l$ | superficial liquid velocity | [m $s^{-1}$] |
| $_{fm}$ | superficial liquid velocity through filtermedium | [m $s^{-1}$] |
| | distance in cake between 0 and H(t) | [m] |
| x | thickness filtermedium | [m] |

Greek symbols

| | | |
|---|---|---|
| $_{av}$ | average specific cake resistance during filtration exp. | [m $kg^{-1}$] |
| | porosity | [-] |
| $_0$ | porosity at $p_s$=0 | [-] |
| $_s$ | solidosity | [-] |
| | compressibility coefficient | [-] |
| | viscosity filtrate | [Pa s] |
| $_s$ | viscosity solids skeleton | [Pa s] |
| | compressibility coefficient | [-] |
| $_l$ | density filtrate | [kg $m^{-3}$] |
| $_s$ | density solids | [kg $m^{-3}$] |
| | solids material coordinate | [m] |
| $_{max}$ | maximum solids coordinate | [m] |

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