Simulation of sludge dewatering on belt filters
Morten Lykkegaard Christensen, Rasmus Rosenlund Petersen and Lars Bjerg Jørgensen

ABSTRACT
A mathematical model for belt filters was developed to determine optimum load rate and belt speed during drainage of flocculated biological sludge. Numerical simulations were performed for belt filters with and without plows, and the model fit experimental data well. Experiments showed that highly compressible cakes were formed during drainage, which was important. Due to cake compression, the final sludge dry matter content increased with load rates as long as the drainage time was sufficiently long. The dry matter content could be increased by stacking the cake at the end of the process. An optimum load rate was found. At high load rates, the drainage time was too short and the dry matter content decreased with load due to high cake resistance. The resistance could be lowered by mixing cake and suspension during the process.

Key words | activated sludge, compressibility, drainage, flocculation, wastewater

INTRODUCTION
Activated sludge is produced in large quantities during biological treatment of wastewater. It contains a high amount of water and is usually dewatered before it is used as an agricultural fertilizer, incinerated or deposited on the landfill (Dirkwzager et al. 1997). Different techniques have been used for mechanical dewatering of sludge, e.g. belt filters, filter presses, rotary drum filters, and decanter centrifuges (Wakeman 2007). The dewatering process is expensive and energy demanding; hence, if the efficiency of the dewatering process can be improved, it will have a high impact on the overall cost of wastewater treatment. However, design and operation of equipment are based on empirical knowledge as no adequate model descriptions of the dewatering processes exist, and it is important to get a better theoretical understanding of the dewatering process to improve the efficiency of the process.

The theory for many types of separations has been developed for suspensions of inorganic particles and not activated sludge. As opposed to inorganic particles, activated sludge consists of primary particles (0.5–5 μm) and sludge flocs (25–200 μm) (Snidaro et al. 1997; Mikkelsen 1999). The flocs are highly porous, having a fractal-like interior structure with small pockets of water of various size inside the flocs (Li & Ganczarczyk 1990; Snidaro et al. 1997). Thus, sludge forms highly compressible cakes during e.g. pressure filtration where the filtrate flux is almost pressure independent (Sørensen & Hansen 1993; LaHeij et al. 1996; Christensen & Keiding 2007). However, the mathematical models for gravity drainage do not include cake compression (Nenniger & Storrow 1958; Wakeman & Vince 1986; Severin & Grethlein 1996; Severin et al. 1999) although it might be expected that compressible cakes are formed and, further, that this affects the drainage process.

This paper presents a method for measuring cake properties during drainage. A mathematical model, which includes cake compression, was developed to simulate dry matter content of the drained sludge as function of load rate and belt speed for belt filters both with and without plows.
METHODS

Flocculated biological sludge from Aars wastewater treatment plant was analyzed. The plant treated industrial and domestic wastewater from Aars and the surrounding area in the amount of roughly 70,000 PE. Approximately 80% of the wastewater originated from industry that processed agricultural products. Phosphorus was removed chemically by adding iron chloride to the wastewater. Organic materials and ammonia were removed biologically. Sludge from both processes was mixed and flocculated with polyacrylamide (Aquaflok CG-156, Dansk Aquakemi A/S, Denmark). The charge density of the polymer was determined to be 3.6 meq/g by using the colloidal titration method (Terayama 1952). Approximately 45 kg of flocculant was added per m$^3$ dry matter sludge. The dry matter content of the flocculated sludge was measured to be 2.3 ± 0.1%w/w. At the plant, the flocculated sludge was drained and consolidated using a belt filter press. Only sludge drainage was studied in this paper. A sketch of the belt filter is shown in Figure 1, and some data are given in Table 1. During the process, samples were taken out from the belt filter at the position shown on the figure, i.e. as function of belt length (sample I, II up to V) and belt width (A, B and C). Each sample consisted of 20–80 g sludge and was taken carefully up from the belt. Experiments were done on belt filters both with and without plows. The belt speed on the full-scale filter press was fixed at 2.57 m/min. The load rate was changed until the drained sludge looked dry. The drainage process was quite sensitive to load, and the empirical found load rate was close to the optimum load rate as confirmed by model simulation.

Cake compressibility was determined from bench-scale experiments. A sketch of the equipment used is shown in Figure 2. The inner diameter of the cylinder was 53 mm, and a filter paper No. 5A (Advantec, Tokyo, Japan) was placed at the bottom of the cylinder. Five experiments were performed by adding 50, 100, 200, 300, and 400 ml of flocculated sludge, respectively, to the cylinder. The weight of the filtrate was measured during drainage and the dry matter content of the cake at the end of the experiment. The dry matter content was determined gravimetrically by measuring the weight of the samples before and after drying at 104°C for more than 24 hours.

SIMULATION OF DRAINAGE PROCESS

The drainage process was simulated numerically. The key parameter was the dry matter content of the drained sludge, which was determined as a function of volumetric load and

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Data for belt filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading rate</td>
<td>20 m$^3$/h</td>
</tr>
<tr>
<td>Belt speed</td>
<td>2.57 m/min</td>
</tr>
<tr>
<td>Effective belt width</td>
<td>1.7 m</td>
</tr>
<tr>
<td>Effective belt length</td>
<td>3.7 m</td>
</tr>
<tr>
<td>Rows of plows</td>
<td>9</td>
</tr>
<tr>
<td>Position of rows relative to inlet</td>
<td>38, 70, 102, 135, 180, 217, 253, 285, 316 cm</td>
</tr>
<tr>
<td>Plows per row</td>
<td>5 or 6</td>
</tr>
<tr>
<td>Plow width</td>
<td>7 cm</td>
</tr>
<tr>
<td>Plow depth</td>
<td>9 cm</td>
</tr>
</tbody>
</table>
belt speed. The dry matter content was determined from the drainage rate, which decreased from the inlet to the outlet. Moreover, the drainage rate was calculated by using Darcy’s law:

$$q = \frac{\Delta P}{\mu(R_c + R_m)}$$

where $\mu$ (Pa·s) is the filtrate viscosity, $R_c$ and $R_m$ (m$^{-1}$) is the cake and filter resistance, respectively, and $\Delta P$ is the liquid pressure drop across the cake and filter media. The pressure drop was calculated by using Equation (2) assuming that the dry weight of the cake was low compared with the weight of the suspension and the wet cake:

$$\Delta P = \frac{\rho g H}{A_{\text{eff}}} - p_s^{\text{top}}$$

where $\rho$ (kg/m$^3$) is the density of the suspension, $g$ (m/s$^2$) is the gravitational acceleration, $p_s^{\text{top}}$ (Pa) is the structure pressure at the top of the cake, and $A_{\text{eff}}$ (-) is the ratio between effective and total filter area. Furthermore, $H$ (m) is the suspension height, and $H = H_0 - v$, where $H_0$ (m) is the initial height, and $v$ (m) is the specific filtrate volume.

For the belt filter without plows, $A_{\text{eff}}$ was set to 1. For the belt filter with plows, the plows scraped off sludge from roughly one-third of the filter area. Thus, $A_{\text{eff}}$ was set to 1 until the sample reached the first row of plows, after which $A_{\text{eff}}$ was set to 0.66. The structure pressure at the top of the cake was zero during cake built up (Tiller & Kwon 1998). When the suspension was fully drained and only the cake remained on the media, air reached the surface of the cake. Air did not penetrate the cake; instead $p_s^{\text{top}}$ increased, and the cake collapsed. The structure pressure is a function of the dry matter content of the cake and was calculated by using Equation (3) (Tiller & Kwon 1998):

$$p_s = p_a \left( \frac{\phi}{\phi_0} \right)^n - 1$$

where $\phi$ is the dry matter content, and $\phi_0$, $p_a$, $n$ are empirical parameters. $n$ denotes the degree of compressibility (Tiller & Kwon 1998). If the dry matter content at the top of the cake is known, $p_s^{\text{top}}$ can be calculated. However, this was not possible. Instead, it was assumed that the dry matter content was constant throughout the cake. By doing this $p_s^{\text{top}}$ was overestimated but previous results show that this only has little impact on the simulation results (Christensen et al. 2010).

The cake resistance was calculated from Equation (4):

$$R_c = \alpha \omega$$

where $\alpha$ (m/kg) is the specific cake resistance and $\omega$ (kg/m$^2$) is the dry mass of the cake per area. Two extremes were simulated: (1) one in which it was assumed that the specific cake resistance was constant, and (2) one in which it was assumed that the specific cake resistance increased proportionally with initial volumetric load.

The amount of the cake deposited on the filter media was calculated from Equation (5) (Wakeman & Tarleton 1999):

$$\omega = \frac{H_0 C_{\text{feed}}}{(H_0 - v) - mH_0 C_{\text{feed}} \rho_L}$$

where $\nu$ (m$^3$/m$^2$) is the specific filtrate volume, $C_{\text{feed}}$ (kg/m$^3$) is the solid concentration in the feed suspension, $m$ (-) is the mass of wet cake divided by the mass of the dry cake, $\rho_L$ (kg/m$^3$) is the liquid density, and $\nu^*$ (m$^3$/m$^2$) is the...
the specific filtrate volume measured at the previous plow. 

\( v^* = 0 \) before sludge reaches the first plows and for belt filters without plows.

The filtrate volume was calculated from the filtrate flux by using Euler’s method, i.e. 

\( v_{k+1} = v_k + hq \), where 

\( h \) (s) is the time step, 

\( h = s \Delta x \), 

\( s \) (m/s) is the belt speed, and 

\( \Delta x = 0.5 \text{mm} \).

From the filtrate volume, the dry matter content \((\phi \text{ (g/g)})\) was calculated by using Equation (6):

\[
\phi = \phi_0 \frac{H_0}{H_0 - v(t)} \quad (6)
\]

where \( \phi_0 \) (g/g) is the dry matter content in the feed.

RESULTS

Figure 3A shows the calculated average dry matter content of sludge during drainage on a bench-scale apparatus. All experiments except one were stopped when the weight of the filtrate stayed constant. The one with the highest volumetric load was stopped before that, because of the slow drainage rate. It was found that the required drainage time increased with volumetric load; most rapidly at volumetric loads higher than 0.94 m\(^3\)/m\(^2\). For experiments in which the drainage process was finished before the experiment was stopped, the structure pressure was constant throughout the cake and could be calculated from the weight of the wet cake. The pressure is plotted as a function of the measured dry matter content of the drained cake (Figure 3B). Equation (3) was fitted to the experimental data, and it was found that \( \phi = 4.7 \left(1 + \frac{p_s}{60}\right)^{0.29} \). The degree of compressibility was determined to be 0.29, and the cake was therefore highly compressible according to Tiller & Kwon (1998).

A full-scale belt filter was tested by measuring the dry matter content of the sludge on the belt filter. Flocculated biological sludge was added to the filter. The belt speed was 2.57 m/min, and samples were taken out at different positions on the belt filter. The distance between the inlet and the sampling point was measured, and the residence time of the sample calculated. Samples were taken out (1) at the border of the belt, (2) at the center of belt, and (3) in between the center and border. Figure 4 shows the measured dry matter content of the samples. As expected, the dry matter content of the sludge increased with residence time. Further, the dry matter content varied from the center to the border of the belt filter. Thus, the drainage rate varied from the center to the border. At the end of the drainage process, the difference in dry matter content levelled out. It was observed that the plows scraped off the cake, and part of the filter media was bared after the plow. Thus, not all of the filter media area was used during the drainage process. The distance between the plows on the rows varied, and no plows were placed at the border of the belt. Further, the initial distribution of the sludge varied from the center to the border of the belt filter. The variation of dry matter content was ascribed to these factors. As the dry matter content varied with the width of the belt filter, it was decided for the next analyses to take out samples at the center of the belt filter (59 cm from the border of the belt).
In order to test the effect of the plows, two experiments were performed on the full-scale belt filter: one with and one without plows. Figure 5 shows the dry matter content as a function of residence time. The first row of plows had almost no effect on the drainage rate as opposed to the next eight rows of plows, which had high impact on drainage. The dry matter content increased significantly for belt filters with plows; however, a cake of a given thickness was required before the plows had any effect.

The drainage processes on the belt filter were simulated to study how load rate and belt speed influence the drainage process. In order to do this, the relationship between equilibrium dry matter content and structure pressure had to be known; data from the bench-scale experiment were therefore used. The equilibrium dry matter content was only a function of wet cake weight, and thus cake compressibility found in the bench-scale experiment could be used for belt filter simulation. The average specific cake resistance also had to be known. Nevertheless, it was observed that the required drainage time was higher during the bench-scale experiment than during the full-scale experiment. This was ascribed to media choice and the turbulence at the inlet during the full-scale experiment. The average specific cake resistance of the cake was therefore estimated from the full-scale experiment without plows. The drainage model was fitted to the measured dry matter content, and the average specific cake resistance was estimated to be $1.2 \times 10^9$ m/kg.

The drainage experiment with the belt filter with plows was then simulated using the experimental determined input parameters. The result is shown in Figure 5.

The effect of varying the load rate and the belt speed was modeled in order to study the difference between drainage of non-compressible cakes ($\alpha$ constant) and highly-compressible cakes ($\alpha$ increases proportional with pressure). Figure 6A shows the calculated dry matter content of the drained sample as a function of load rate. The optimum load rate was estimated to be $20 \text{ m}^3/\text{h}$ if average specific cake resistance was constant and $18 \text{ m}^3/\text{h}$ if the resistance increased proportionally with pressure. Above optimum, the dry matter content dropped most rapidly with load rate if the resistance increased proportionally with pressure. Figure 6B shows the dry matter content as a function of belt speed. The optimum belt speed was estimated to be $2.6 \text{ m/min}$ if average specific resistance increased proportionally with pressure. If resistance was constant, the dry matter content of the drained product increased with decreasing belt speed. No optimum was found.

**DISCUSSION**

Flocculated biological sludge forms highly compressible cakes during drainage, i.e. highly compressible cakes are formed not only at high pressure ($>50 \text{ kPa}$) (Tiller & Kwon 1998) but also at low pressure ($<1 \text{ KPa}$). This is important
(1) because the equilibrium dry matter content then increases with structure pressure and therefore with the final weight of the wet cake, and (2) because the average specific cake resistance of highly compressible cakes increases almost proportionally with structure pressure. As a consequence, both drainage time and equilibrium dry matter content strongly depend on the volumetric load. The structure pressure is a function of load rate, belt speed, media resistance and filtrate volume, and if the media resistance is negligible, drainage time increases with the squared volumetric load for highly compressible materials. For non-compressible materials, it only increases proportionally with volumetric load.

A full-scale belt filter has been studied with and without plows. The drainage time is significantly reduced when plows are used. The plows remove cake from the media and partly mix the solid material with the suspension. Hence, total cake resistance decreases and drainage rate increases. As cake is removed from part of the media, the filter area is not fully used. This is a problem during drainage. However, at the end of process, stacking of the cake actually increases the dry matter content of the drained sludge because the cake collapses more after stacking.

The drainage process has been simulated to study how load rate and belt speed affect the dry matter content of the drained sludge. An optimum load rate and belt speed exists for highly compressible cake (Figure 6A,B). At low load rates, the equilibrium dry matter content of the cake is reached at the outlet of the belt filter. Hence, the dry matter content of the drained sludge increases with wet cake weight, and therefore the dry matter content increases with feed concentration as well as load rate. At high load rates, the sludge is not fully drained. Drainage time increases with load rate, and for highly compressible cake, the resistance increases proportionally with pressure; the dry matter content of the drained product therefore decreases rapidly for highly compressible cakes. Belt speed also influences the drainage process. Both drainage time and wet cake weight increase with belt speed. If the average specific cake resistance is independent of pressure, drainage time increases proportionally with volumetric load. Thus, there is enough time for draining the extra volume of material laid out per filter area at low belt speed. This is not case if the resistance increases proportionally with pressure. The drainage time then increases proportionally with square volumetric load/filter area. Thus, at low belt speed, there is not enough time for the drainage process, and the dry matter content of the drained sludge is therefore low. Above the optimum belt speed, the cake is thin, and media resistance starts to be important for the drainage process. The dry matter content of the thin cakes is low because the cake does not collapse much under the low weight of the cake.

Some addition points can be drawn from the study. The plows do not have any effect on the drainage time before a cake is built up. In this experiment, the first row of plows had almost no effect on the drainage process. Later, plows scrape the cake away from the filter, and the drainage rate can be increased if the sample is distributed and the filter...
area fully utilized after the plows. At the end of the belt filter, it is better to stack the material to get a high dry matter content of the drainage sample.

CONCLUSIONS

Drainage of flocculated biological sludge on belt filters has been simulated and the result compared with experimental data. Cake compression is adopted in the model because bench-scale experiments show that highly compressible cakes are formed during drainage. The model can be used to find the optimum belt speed and load rate. Below optimum load rate, final dry matter content is determined by cake compressibility. A higher dry matter content can therefore be achieved by stacking the cake at the end of the process. Above optimum load rate, final dry matter content is determined by cake resistance and decreases dramatically with decreasing load rate and increasing belt speed. In this case, final dry matter content can be increased by mixing the suspension during the drainage process.

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