SIMULATION OF LIQUID PHASE ACCUMULATION FOR THE CENTRIFUGAL DEWATERING OF ACTIVATED SLUDGE

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Centrifugation of activated sludge is a frequently used dewatering process but, in spite of this, there is a need for a fitting function for moderate and high sludge concentrations. Liquid phase accumulation kinetics during centrifugation may be used as a source of information about the sedimentation properties and the governing mechanism during cake formation. For this purpose, activated sludge at different concentrations was investigated on a laboratory centrifuge with a centrifugation factor of 2667. The following sludges were used in the experiments:

1. Activated sludge from a thickener (with and without flocculant treatment)
2. Sludge taken after an industrial centrifuge decanter, treated with Flottweg Z62-4 flocculant and collected from a dumping pound
3. Sludge (2) after anaerobic treatment
4. Sludge (2) with a dispersed solid additive.

Using the experimental data for an asymptotical analysis, a dimensionless fitting function was obtained that adequately describes the dependence of liquid volume vs. time for the centrifugation of activated sludge. For the highly concentrated sludge it was found that the dewatering occurs through cake compression. Analysis of deformation models leads to the conclusion that for the compressible cake it is necessary to introduce a parameter characterising the cake plasticity dependence on the centrifugation time. The developed model was validated by fitting numerous experimental data. The main advantage of the proposed model is the possibility to fit the liquid phase accumulation kinetics during centrifugation over a wide range of activated sludge concentration values, from suspensions up to structured and paste-like cake consistency.

INTRODUCTION

The analysis of suspension sedimentation and centrifugation is presented in numerous works[1-4]. The existence of different physico-chemical factors involved in the centrifugal decanting process does not favour obtaining a general solution for the problem. Frequently, models are based on data for defined initial and boundary conditions. Nevertheless, with changing slurry properties, for instance with activated sludge, model predictions can significantly deviate from experimental measurements. This is the reason for the application of semi-empirical models for sedimentation and centrifugation[5]. In many industrial applications information about the "dewatering potential" of a centrifugation process at certain technological conditions is required, e.g. sludge concentration, centrifugation factor, treatment condition, etc. Laboratory centrifuge tests, where experiments are performed up to the point where equilibrium between the sediment and fugate is achieved, may be used to get this data.

Centrifugation kinetics can be represented in the form of the fugate (liquid phase) volume V, accumulation vs. time of centrifugation t, or in a normalised volume form as $v = V/V_\infty$, where V and V_∞ are the decanted liquid volumes at time t and at equilibrium, respectively. Applying the normalised volume v, the simplest kinetic dependence[6] has the form

$$v = 1 - \exp(-k_1 t) \tag{1}$$

where k_1 is a coefficient comprising parameters dependent on the centrifugal force and sludge properties. The centrifugal force is usually represented in the form of the centrifugation factor

$$K_c = \frac{\omega^2 r}{g} \tag{2}$$

where ω is the rotation speed, r is a radius of rotation, characterised as the distance of a sludge particle at a certain time from the axis of rotation and g is the acceleration due to gravity. As particles are randomly distributed in the suspension at the beginning of the centrifugation process and, when equilibrium is reached, accumulate in the sediment, in industrial applications K_c is considered as an average value.

Another model, proposed for an activated sludge, takes the form of a double exponential decay[7]

$$\frac{dv}{dt} = A\exp(-k_2 t) + B\exp(-k_3 t) \tag{3}$$

where A, B, k_2 and k_3 are coefficients.

Centrifugation of activated sludge is a frequently used dewatering process but, due to the wide range of sludge properties, relations adequately describing the dewatering kinetics data are still missing. There is a need for a fitting function for moderate and high sludge concentrations, in particular, for the liquid phase accumulation kinetics during centrifugation.

EXPERIMENTS

Activated sludge obtained from an industrial wastewater treatment plant at different solids concentrations determined as dry solids (DS) and solid composition content was investigated at room temperature. The wastewater treatment plant treats sewage water from a petroleum refinery plant and municipal wastewater from a city with a population of around 70,000. The characteristics of the used sludge were:

1. activated sludge from the thickener (with and without flocculant treatment)
2. sludge samples taken after the industrial centrifuge decanter, treated with Flottweg Z62-4 flocculant and collected from the dumping pound
3. sludge (2) with and without food waste after anaerobic treatment
4. sludge (2) with a dispersed solid additive.

Centrifugation experiments were performed on a laboratory tubular centrifuge with a 30 cm diameter rotor and 8 tubes each having a sample volume of 30 ml (sample height = 4.5 cm). The average centrifugation factor K_c was 2667.

RESULTS AND DISCUSSION

Analysis of the Centrifugation Kinetics and Model Determination

Based on the experimental data obtained (and presented later in Figures 6, 8 and 9) the following assumption was made, the settling of the solid phase and cake compaction depends on the hindered settling velocity and sediment compression. Due to the applied centrifugal force, a primary cake skeleton from particular aggregates and flocs is formed leading to free water being displaced from the space between the aggregates/flocs (inter-floc liquid). This stage is followed by compaction of the sediment with the water being displaced from the pores of the flocs (intra-floc liquid) by a filtration mechanism until an equilibrium condition is reached at $t \to \infty$.

The liquid volume for hindered sedimentation and sediment dewatering can be represented in the form $V \propto t^n$, where $n \leq 1.0$. Therefore, in log-log coordinates, the kinetics of liquid accumulation must have a linear dependence $\log(V) \propto n\log(t)$ if the process is controlled by a single mechanism, or comprise a series of different linear functions if during dewatering one mechanism changes to another. This assumption was confirmed for different types of activated sludge. In Figure 1, for example, the dependence of the liquid volume on time for different types of activated sludge is shown. It is seen that the observed dependences are well fitted by linear relationships.

A model that may cover the entire range of concentrations for activated sludge is developed below. In this model, the liquid phase volume V obtained during centrifugation is assumed to be the main variable. Using asymptotical analysis[8], in the function form $F(t,V)$ that satisfies the conditions

$$\lim_{t \to 0} F = F_0(V) \neq \infty \text{ and } \lim_{t \to \infty} F = F_\infty(V) \neq \infty$$

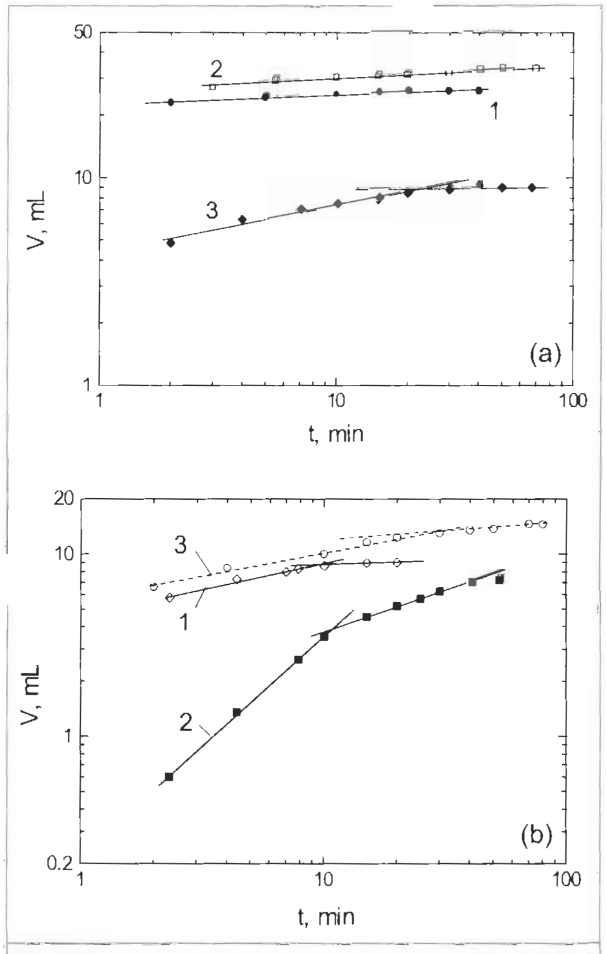

Figure 1: Experimental data for the centrifugation of activated sludge. (a): 1 – with 1.6 % DS, 2 – treated by Sedipure flocculant (11.9 mg/g DS), 3 – centrifuged on an industrial decanter after anaerobic treatment with 16.64 % DS. (b): 1 – centrifuged on an industrial decanter with 10.6 % DS, 2 – the same with 11.67 % DS, 3 – the same with 11.7 % DS + cement to the amount of 50 % DS.

the dimensionless general fitting function is obtained[8]

$$\frac{V}{V_\infty} = v = \frac{(t/t^*)^p}{\left(a+(t/t^*)^p\right)} \qquad (4)$$

where, in our case, $F_0(V) = 0$ and $F_\infty(V) \equiv V_\infty$; $v \in [0, 1]$; a, t^* and p are the model parameters. At $(t/t^*)^p \to \infty$, $v \to 1.0$.

Due to the specific properties of the activated sludge, parameters a and t^* are variable. For instance, the activated sludge settling properties are affected by the coagulation/flocculation pretreatment, the ratio of organic/non-organic components in the solid phase, etc. and, therefore, the settling kinetics will be different. However, if the centrifugal dewatering plays a key role, the settling kinetics in the coordinates $v - t$ will result in a series of similar curves (see Figure 2). Assuming equation (4) to form the basis of the model, the values of the model parameters a, t^* and p are obtained below for different modelling approaches.

Centrifuge Settling

Based on the analysis of the settling process, it may be considered that in the initial stage of centrifugation a dependence $V\ \alpha\ (V_\infty - V)t$ may be applied. Hence, the volume of fugate obtained can be represented as:

$$v = k_s(1-v)t \qquad (5)$$

where k_s is a parameter dependent on the average centrifugal factor (K_c) and sludge properties, has the dimension of $[1/t]$ and can be considered as the process velocity constant.

As follows from equation (5), the experimental data must be fitted by the relation $v/(1-v)\ \alpha\ t$, at least in the initial dewatering stage. Figure 3 presents the experimental data for the activated sludge centrifugate together with the expected linear trend. Rearranging equation (5) gives the equation for hindered settling:

$$v = \frac{k_s t}{1+k_s t} \qquad (6)$$

Comparing equations (4) and (6), the following values of the model parameters are found: $a = 1.0$, $p = 1.0$, and $t^* = 1/k_s$. At the initial settling stage, when $k_s t \ll 1$, $v \approx k_s t$. Moreover, if $t = t^*$ then $v = 0.5$, hence, parameter t^* corresponds to the time when $v = 0.5$ ($V = V_\infty/2$).

Centrifugal Squeezing

From the structured cake, squeezing under centrifugal force can remove an additional volume of liquid. In this dewatering phase the cake porosity becomes a function of time. The dewatering for highly concentrated sludge occurs as cake compaction with a changing plasticity. Analysis of deformation models

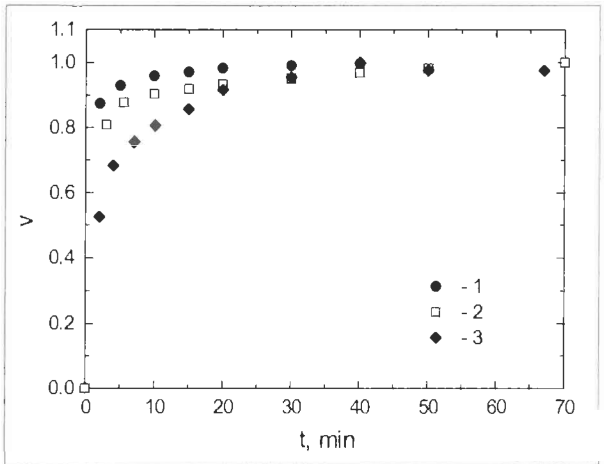

Figure 2: Dependence of v on t for the activated sludge presented in Figure 1(a).

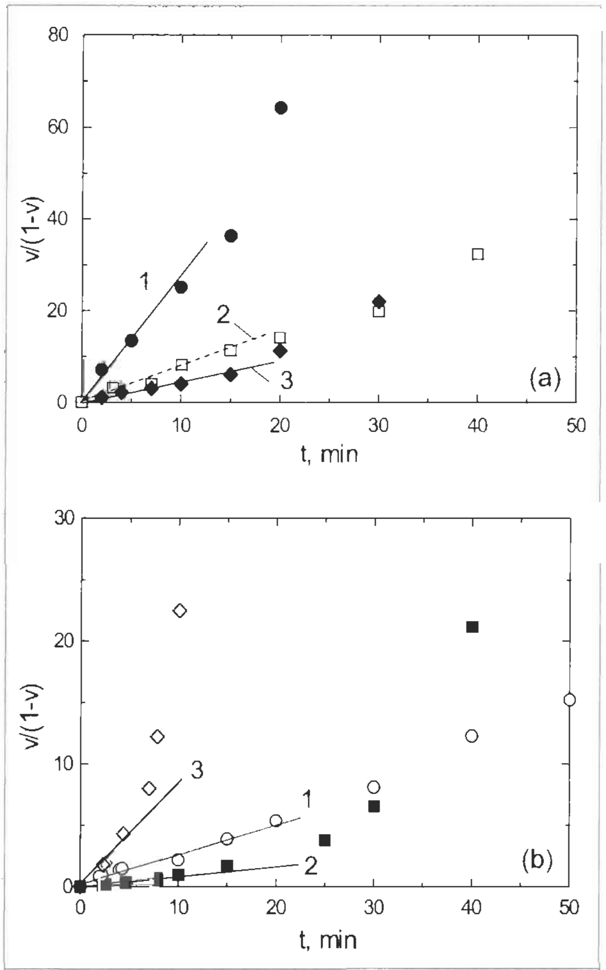

Figure 3: Experimental data and linear relations for $v/(1-v)$ vs. t obtained from the data presented in Figure 1 (line legends also shown in Figure 1).

leads to the conclusion that for the compressible cake, the time coefficient t^* becomes dependent on the dewatering time t. It is possible to assume $t_p^* \alpha t^m t^* = t^m/k_s$, where $0 \leq m \leq 1$ is the parameter that characterises the cake plasticity dependence on the centrifugation time. For the case of $p = 1.0$, equation (4) becomes:

$$v = \frac{k_s t^{1-m}}{1 + k_s t^{1-m}} \tag{7}$$

When $m = 0$ then $t_p^* \equiv t^*$, equation (7) becomes the hindered settling relation (6). The value of m can be calculated from the dewatering kinetics data at any i-th (t_i, v_i) point by:

$$m = 1 - \frac{\log\left(\dfrac{v_i}{(1-v_i)k_s}\right)}{\log(t_i)} \tag{8}$$

or determined by a fitting procedure.

The effect of the parameters $t^* = 1/k_S$ and m on v is shown in Figure 4. As can be seen, with an increase in the hydraulic resistance (i.e. increase of $1/k_S$) the time needed to reach a defined centrifugate volume increases and the initial dewatering velocity decreases.

In the initial dewatering stage, the inequality $k_S t^{1-m} << 1.0$ is valid and equation (7) becomes

$$v = k_s t^{b_1} = k_s t^{1-m} \tag{9}$$

Equation (9) has similarities with the empirical filtration equation $V = kt^b$, where the parameter b characterises the filtration complexity (for instance, cake pores blocking) and is in the range 0.4 – 0.98. The limiting value $b = 1.0$ corresponds to the permeation of pure liquid through a stationary cake (washing regime). Parameter b_1 has a similar meaning and, therefore, when $m = 0$ then $b_1 = 1.0$ and the dewatering process in this condition is characterised by liquid removal from the inter-particle (inter-floc) space.

At $b_1 < 1.0$, the dewatering process occurs as the squeezing of structured cake aggregates with a corresponding change in cake porosity with time and the release of intra-floc liquid. Knowledge of the dewatering velocity dv/dt is important for process control and optimisation. Dewatering velocity w is obtained from equation (7) at $m > 0$:

$$w = \frac{dv}{dt} = \frac{k_s(1-m)}{t^m\left(1 + k_s t^{1-m}\right)^2} \tag{10}$$

When $m = 0$, equation (10) describes the dewatering velocity for the hindered settling regime and $w = k_S/(1 + k_S t)^2$.

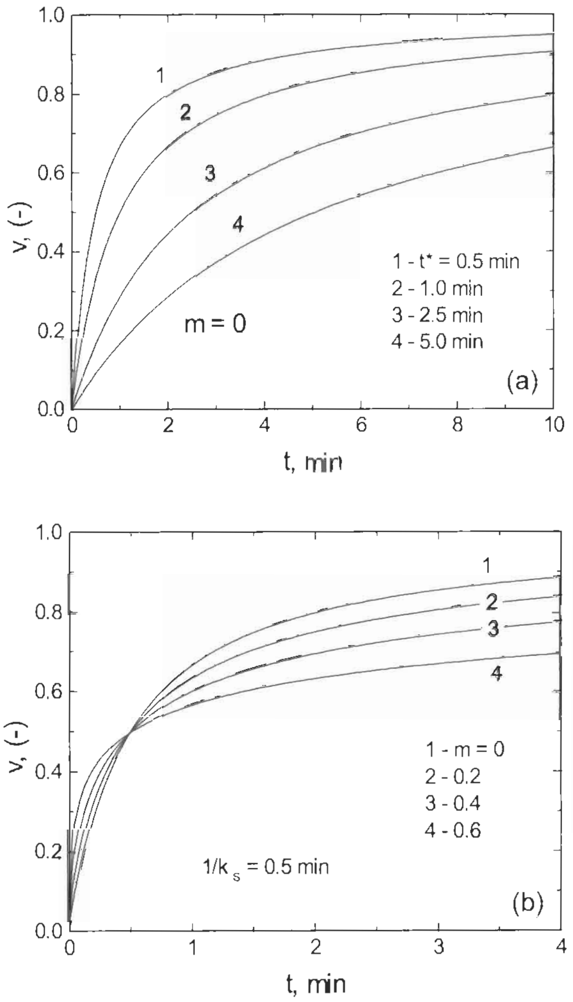

Figure 4: Dependence of v on t^* at (a) $m = 0$, hindered settling regime, and (b) at different m, $1/k_s = 0.5$ mins., squeezing regime.

In Figure 5 the dependence of dv/dt on the dewatering time is presented (a) at $k_S = 1.0$ (1/min), for different values of m and (b) for different regimes, respectively. The effect of variation is shown in Figure 5(b) at $m = 0$ and 0.2. From Figure 5, it follows that the dewatering kinetics are characterised by two periods of moderate and fast reduction of the dewatering velocity w dependence on k_S and m. The considered model confirms conventional observations that the dewatering efficiency increases with $m \rightarrow 0$ and with the reduction of the sediment (cake) hydraulic resistance $1/k_S$.

Figure 6 represents the dependence of the decanted fluid volume on time, for activated sludge at low and moderate solid concentrations (DS). In these situations

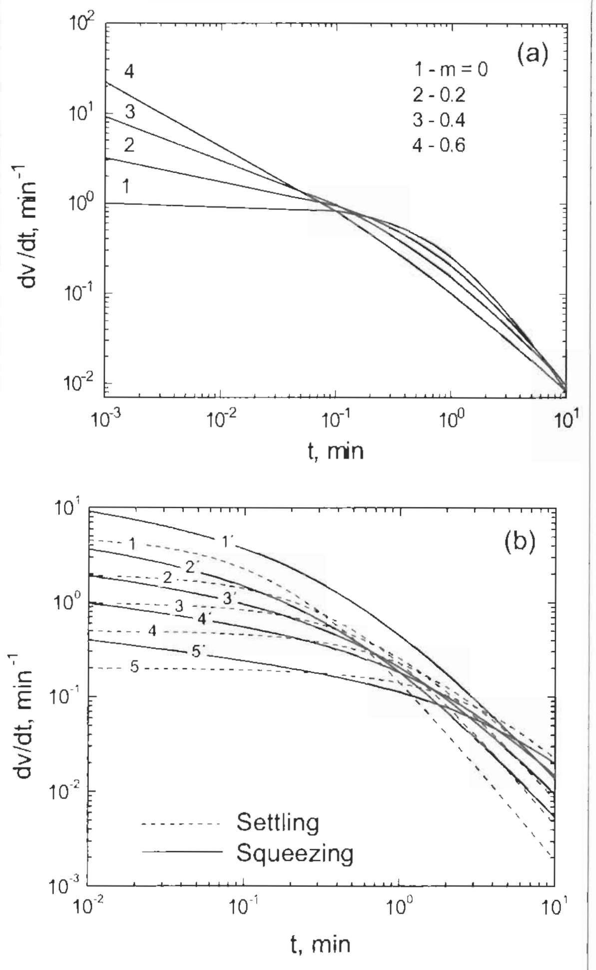

Figure 5: Dependence of dv/dt on *t*, equation (10). (a): k_s = 1 min^{-1} for different values of *m* and (b) effect of k_s on dv/d*t*; curves 1–5, *m* = 0 (settling regime) and curves 1′– 5′, *m* = 0.2 (squeezing). Values of k_s are:1 and 1′ – 5.0; 2 and 2′ – 2.0; 3 and 3′ – 1.0; 4 and 4′ – 0.5; 5 and 5′ – 0.2.

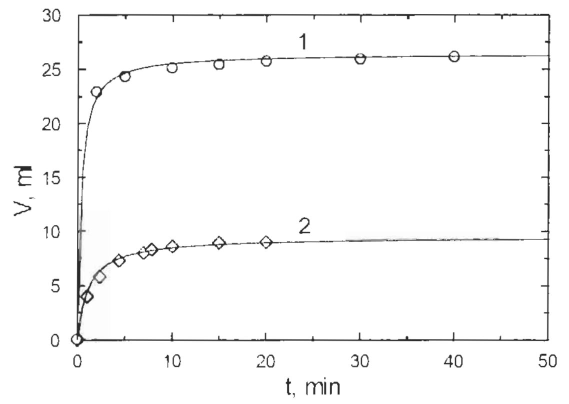

Figure 6: Dependence of the decanted fluid volume on *t* for activated sludge with different DS: 1 - 1.8% and 2 - 10.6%. Points correspond to experimental data and lines to fitting of the data according to equation (6).

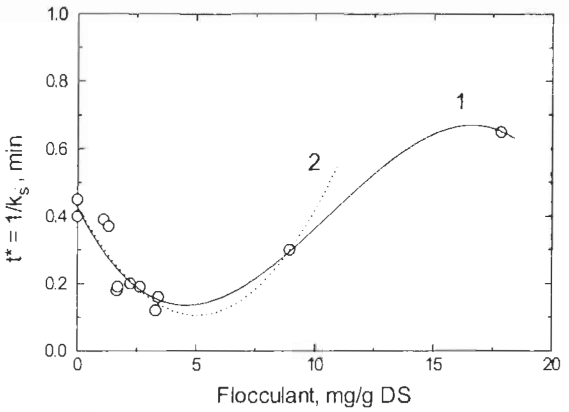

Figure 7: Dependence of t^* (from equation 6) on flocculant concentration for activated sludge with 2% DS. Lines 1 and 2, are respectively, cubic and square fitting functions.

there is no plasticity effect.

The dependence of t^* = 1/k_s on the flocculant dosage is given in Figure 7 together with corresponding fitting functions. As may be seen, the parameter t^* is well correlated with flocculant concentration making it possible to define the optimal dosage for maximum dewatering of the sludge.

The validity of the model for high concentration slurry, as described by equation (7), is shown in Figure 8 for anaerobic treated mixtures of activated sludge and potato peels. The volumetric proportion between the sludge and peels is 1:1. Samples 2 to 4 were treated by using Sedipure flocculant with respective dosages of 8.7, 5.4, and 4.8 g/kg DS. Centrifuged slurries are represented by a non-homogeneous structured system that significantly hampers the dewatering process. Due to the complexity of the direct determination of the plasticity parameter for industrial grade activated sludge, the values of *m* were obtained by a non-linear least squares fitting procedure for the model described by equation (7) as 0.25, 0.28, 0.4, and 0.53 and these correspond to the experimental situations described in Figure 8 as (1) to (4). The model was also evaluated using published data[9,10], which is also shown in Figure 9. Figure 9(b) shows results for the flocculated activated sludge with 8.3% DS[10] treated with different dosages of flocculant.

The dependence of 1/k_s on DS is shown in Figure 10 (a). An increase in the parameter 1/k_s is observed until 7–8% DS activated sludge is reached after which it remains constant for larger DS values. The data is fitted by the function

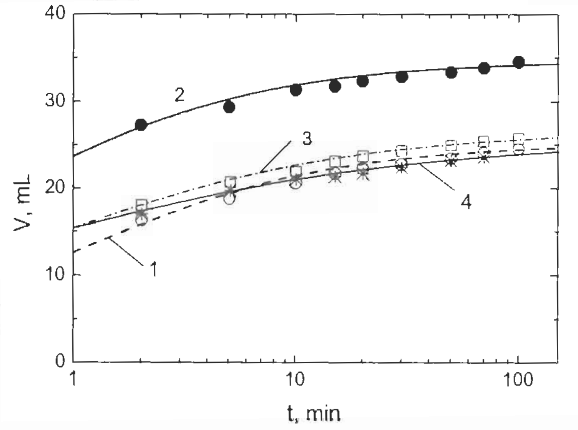

Figure 8: Centrifugation kinetics of an anaerobic treated mixture of activated sludge and potato peel. Points correspond to experimental data and lines to data fitting according to equation (7) for different situations. 1 – total organic fraction 0.47 in 5.78% DS ($m = 0.25$); 2 – same as 1 treated by flocculant ($m = 0.28$); 3 – organic fraction 0.26 in 28.58% DS ($m = 0.4$); 4 – organic fraction 0.25 in 31.99% DS ($m = 0.53$).

$$\frac{1}{k_s} = \frac{1.512}{1 + \dfrac{1}{\exp\left((\mathrm{DS} - 3.4)/0.79\right)}}$$

with a regression coefficient of 0.973. It was determined that up to 7–8% DS, the value of the parameter m for activated sludge dewatering in a centrifuge can be assumed to be to zero. Starting from 7–8% DS, a transition from a settling regime to the filtration (squeezing) regime with $m > 0$ is observed which corresponds to the qualitative change in the cake structural properties. Moreover, experiments show that anaerobic treatment of highly concentrated slurry or when a high amount of organics is present in the solid phase at more than ~5% DS leads to the parameter value $m > 0$ (see Figure 10(b), branch (II)).

CONCLUSION

Using asymptotical analysis, a fitting function was obtained that describes the centrifugation of activated sludge with a high solid phase concentration. For this case it was found that dewatering occurs due to cake compaction. The main advantage of the proposed model is the possibility to fit liquid phase accumulation kinetics during centrifugation for a wide range of the activated sludge solids concentration, from suspension up to structured and paste-like cake consistency. However, the extension of this model to other slurries requires further investigation.

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NOMENCLATURE

a	model parameter in equation (4) (-)
b	power order in filtration formula (-)
b_1	$= 1 - m$
$F(t,V)$	asymptotic function
g	gravity constant (m/s^2)
K_c	centrifugation, average centrifugation factor (-)
k_1	coefficient (1/s)

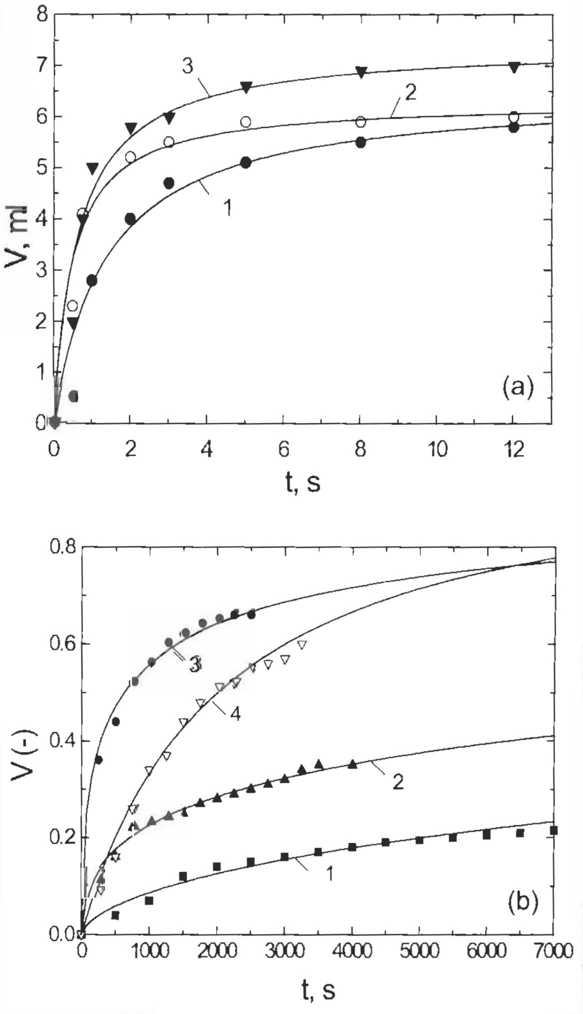

Figure 9: Fitted experimental data V vs. t obtained for activated sludge from (a) Agranonik[9] and (b) Chu & Lee[10]. Points correspond to experimental data and lines to data fitting according to equation (7) for different situations. (a): 1 – 3.5 % DS; 2 – primary settler's sludge, 9.7 % DS; 3 – anaerobic sludge, 4.5 % DS (for these situations $m = 0$ was assumed). (b): 1 – 8.3% DS without flocculant ($m = 0.4$) ; 2 – 8.3% DS with 5 g/kg DS ($m = 0.55$); 3 – 8.3% DS with 25 g/kg DS ($m = 0.5$); 4 – 8.3% DS with 40 g/kg DS ($m = 0$).

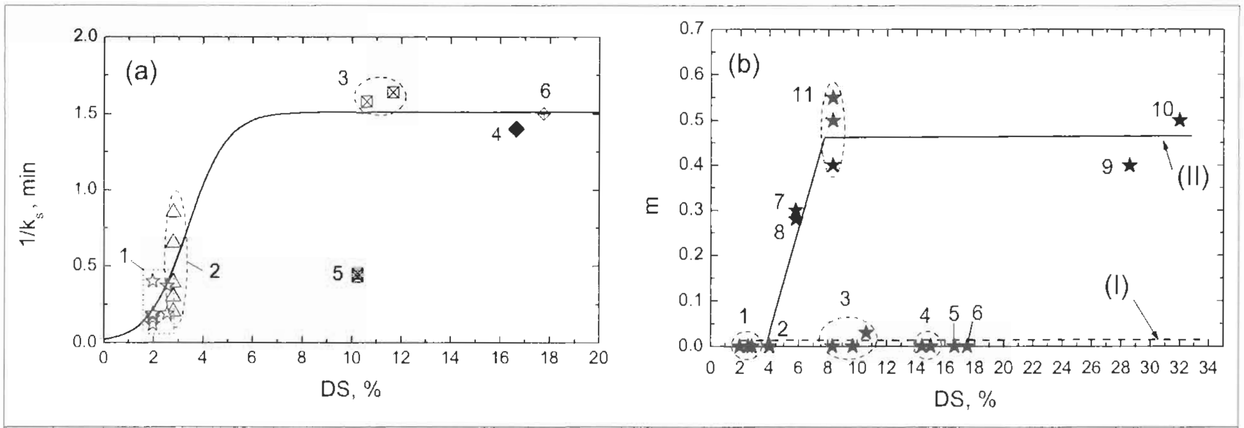

Figure 10: Dependence of (a) $1/k_s$ and (b) m on DS: 1 – activated sludge (AS); 2 – AS treated with flocculant; 3 – AS after industrial centrifuge decanter; 4 – anaerobic AS; 5 – mixture of AS with clay (1:3); 6 – mixture of AS and sludge after decanter (1:1 by volume); 7 – 10 anaerobic treated mixture of AS and potato peel: 7 – 5.78% DS; 8 – the same as 7 treated by flocculant; 9 – 28.58% DS; 10 – 31.99% DS; 11 – data [10].

k_s	parameter in equation (5), dependent on (K_c) and sludge properties (1/s)
m	parameter that characterises the cake plasticity dependence on centrifugation time (-)
n	power value, $n \le 1.0$
p	model parameter in equation (4) (-)
r	radius of rotation (m)
t	time of centrifugation (s)
t^*	model parameter in equation (4) (s)
t_p^*	$\alpha\, t^m t^* = t^m/k_s$
V	fugate (liquid phase) volume (m^3)
V_∞	liquid volume at equilibrium (m^3)
v	$= V/V_\infty$ = normalised liquid volume (-)

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