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The shear sensitivity of activated sludge: an evaluation of the possibility for a standardised floc strength test

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Abstract

The presence of micron-sized primary particles is critical in many solid/liquid separation processes, and characterisation of stability with respect to the degree of dispersion is therefore relevant. Characterisation of floc strength so far has mainly dealt with the size of flocs and not addressed quantification with respect to primary particles. In the present work floc strength was quantified in terms of the shear sensitivity (k_{SS}) as a standardised parameter based on the recent adhesion–erosion model (AE-model). The shear sensitivity quantifies the degree of dispersion for low total solids contents and intermediate turbulent shear rates. It reflects the affinity of adhesion/erosion of primary particles to and from flocs and thus provides a means of characterising the interaction energy between the sludge colloids. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: AE-model; Deflocculation; Degree of dispersion; Erosion; Floc strength; Shear sensitivity; Shear effects; Interaction energy; Adhesion enthalpy

1. Introduction

In wastewater treatment solid/liquid separation processes (clarification and dewatering) are important with respect to both economy and environmental impact on recipients. Separation efficiency is largely affected by the activated sludge structure in terms of the particle size distribution, shape, density and porosity of the particles [1–3] or in particular by the fraction of small (micron-sized) particles [4–6]. Floc strength is important because break-up due to hydrodynamic forces causes a shift in particle size distribution. In spite of the importance, effects of agitation are not well understood and there is a lack of quantitative techniques for floc strength assessment [7,2].

The particle size distribution of activated sludge is bimodal, containing two particle classes, i.e. flocs sized ca. 25–100 μm and free colloids (primary particles) sized ca. 0.5–5 μm [8,9]. Flocs consist of a multitude of bacteria and extracellular polymeric material [10,11]. The primary particles are to a large extent single bacteria, but may contain other colloidal matter. Flocs are the main constituents of sludge by volume and mass [9]. Although the dispersed primary particles only contribute with a small fraction of the total sludge mass in activated sludge, their impact on solid/liquid separation is critical. Due to their small size, they are a source of supernatant turbidity, and they cause blinding during filtration due to clogging of the porous structure formed by the larger particles [12], leading to high specific cake resistance [13–15]. Thus, the extent of primary particle incorporation into flocs seems to have a significant impact on both clarification (turbidity) and filtration. Therefore, the relative magnitude of the two size classes, i.e. primary particle mass to total sludge mass is an important quantity for solid/liquid separation.

The particle size distribution of suspensions is dynamic and affected by turbulent shear [2,16]. Particles may flocculate under low turbulence levels and break up when exposed to high turbulence [8,17,18]. Break-up

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occurs by two mechanisms of differing nature. Fragmentation of flocs into floc fragments causes a shift towards smaller flocs with no change in the primary particle population [8]. Erosion of primary particles from floc surfaces on the other hand, causes a shift in the relative mass of the two particle size classes. In highly flocculated systems, erosion implies a pronounced increase in the primary particle population, whereas the relative change of floc size and mass may be minor. Strength of flocs in terms of ability to resist erosion is therefore relevant in solid/liquid separation processes, where the primary particle number concentration is detrimental. However, as noted by Gregory [7] most methods for evaluating floc strength have dealt only with the change of floc size in response to hydraulic forces [19–22] with very little attention given to the primary particle concentration.

Primary particle concentration in deflocculation was the topic of a recent study by the present authors [23]. Non-linear increasing colloid concentrations were found with increasing solids content or increasing turbulent shear rate (characterised by the root-mean-square velocity gradient, G). The data indicated errors in the earlier model of flocculation–deflocculation balances by Parker et al. [8,17]. Instead, the adhesion–erosion model (AE-model) was suggested by Mikkelsen and Keiding [23] to describe the effects of solids content and turbulent shear on sludge deflocculation based on a macroscopic model of multi-layer adhesion. In the AE-model, sludge adhesion–erosion is considered in analogy to gas–liquid phase transitions, i.e. as a condensation or "self-flocculation" phenomenon. The degree of primary particle incorporation into flocs is described by thermodynamic parameters; i.e. the change in enthalpy (ΔH_{ad}) and Gibb's free energy (ΔG_{ad}) of the adhesion process. From this, ΔG_{ad} of colloid suspensions may be characterised from a series of shear experiments fitted to the AE-model [23]. Such a set-up does, however, consume large amounts of sample, equipment and time. Therefore, there is a need also for less laborious methods for adhesion energy characterisation.

The objective of the present study was therefore to employ the AE-model in the development of a standard method for adhesion energy characterisation based on shear deflocculation. The aim was to maintain a close link to the thermodynamic parameters governing the adhesion–erosion balance, thereby providing a practical method of physico-chemical significance.

2. Theory

2.1. Effects of solids content

Many attempts on modelling the flocculation process have been based on the principles of the early work by von Smoluchowski [24]. This approach considers stochastic collisions between flocs and no break-up, leading to prediction of a continuous particle size distribution and unlimited flocculation as flocculation time increases. This is clearly not the case in practical systems. In reality, some equilibrium degree of flocculation is approached, and at least for some particle systems, this equilibrium is bimodal [25,26,8,9].

For a bimodal particle size distribution, we may consider the primary particles and the flocs as two different chemical species. The process of simultaneous adhesion and erosion may thus be treated in analogy to reversible chemical reactions in which an equilibrium between the two species is established. By this analogy, the equilibrium is expected to depend on both suspended solids concentration and the kinetic energy input. In the AE-model derived by Mikkelsen and Keiding [23], solids concentration is regarded in terms of the total primary particle number concentration n_T, which is equal to the sum of the dispersed primary particle concentration (n_d) and the adsorbed primary particle concentration (n_a). The latter represents the number of primary particles existing in flocs, regardless of the number and size of the flocs. Assuming an upper limit of adhesion and that the adhesion is governed by an average Gibb's energy of adhesion (ΔG_{ad}) allows use of the Langmuir isotherm [27,23]:

$$\Theta = \frac{Kn_{d,\infty}}{1 + Kn_{d,\infty}}, \tag{1}$$

where Θ is the number concentration of adsorbed primary particles (n_a) relative to the maximum number concentration of adsorbed primary particles ($n_{a,max}$), i.e. $\Theta = n_a/n_{a,max}$, K is the equilibrium constant, and $n_{d,\infty}$ is the number concentration of dispersed primary particles at equilibrium. Introducing $n_a = n_T - n_d$ yields the expression [23]:

$$n_T = n_{d,\infty} + \frac{n_{a,max}Kn_{d,\infty}}{1 + Kn_{d,\infty}}. \tag{2}$$

This model is based on multi-layer adhesion in the build-up of flocs, assuming the same average adhesion energy for all layers. The dispersed and aggregated phases may be quantified in terms of number concentration, activity, equivalent turbidity or as mass concentration. The choice of units adopted in Eq. (2) will be reflected in the unit of K, since the product Kn_d has no dimension. If n_T and n_d are quantified in units of volumetric activity, the adhesion Gibb's energy may be estimated from general physical chemistry (e.g. Atkins, 1994 [36]), i.e. $\Delta G_{ad}/RT = -\ln K_a$ (the subscript a indicates an activity based quantity). When any other scaling is used for n_T and n_d, the estimated equilibrium constant would be linked to K_a by a proportionality factor f, so that $K_i = f_i K_a$, (the subscript i denotes quantities based on phase concentrations in unit i).

When arbitrary units of n_T and n_d are adopted in Eq. (2), $\Delta G_\mathrm{ad}/RT$ may not be estimated directly from K_i, since $\Delta G_\mathrm{ad}/RT = -\ln K_a = -\ln K_i + \ln f_i$. However, for comparative purposes this may be avoided as it follows:

$$\ln \frac{K_{i,1}}{K_{i,2}} = \ln \frac{K_{a,1}}{K_{a,2}} = \frac{\Delta G_{\mathrm{ad},2}}{RT} - \frac{\Delta G_{\mathrm{ad},1}}{RT}, \tag{3}$$

where indices 1 and 2 refer to different sludges or different test conditions. Thus, differences in $\Delta G_\mathrm{ad}/RT$ may be estimated from Eq. (3) irrespective of the units adopted for n_T and n_d. For practicality we may adopt mass concentrations to get the expression:

$$m_\mathrm{T} = m_{\mathrm{d},\infty} + \frac{m_{\mathrm{a,max}} K_m m_{\mathrm{d},\infty}}{1 + K_m m_{\mathrm{d},\infty}}, \tag{4}$$

where K_m is the equilibrium constant corresponding to units of mass concentration, m_T is the total solids mass concentration, and $m_{\mathrm{d},\infty}$ is the dispersed mass concentration at equlibrium.

For $K_m m_{\mathrm{d},\infty} \ll 1$, Eq. (4) reduces to

$$\frac{m_{\mathrm{d},\infty}}{m_\mathrm{T}} \approx \frac{1}{1 + K_m m_{\mathrm{a,max}}}. \tag{5}$$

Thus for low values of $K_m m_{\mathrm{d},\infty}$, the dispersed phase fraction of total solids is expected to be constant, i.e. $m_{\mathrm{d},\infty}/m_\mathrm{T} \approx$ constant. This corresponds to the initial linear parts of the model calculations shown in Fig. 1. Thus, by use of Eq. (5) the quantity $K_m m_{\mathrm{a,max}}$ can be estimated from $m_{\mathrm{d},\infty}/m_\mathrm{T}$ for low primary particle concentrations.

The parameter $K_m m_{\mathrm{a,max}}$ is the governing factor for the equilibrium between the adsorbed and the dispersed phases at low total solids contents. In the high solids domain, the equilibrium is increasingly dominated by the value of $m_{\mathrm{a,max}}$ ($m_{\mathrm{d},\infty} \approx m_\mathrm{T} - m_{\mathrm{a},max}$ for $K_m m_\mathrm{d} \ll 1$). Thus, it is not possible to obtain only one number that adequately describes all aspects of the equilibrium described by Eq. (4). K_m is related to $\Delta G_\mathrm{ad}/RT$ and is therefore the most appropriate descriptor of the adhesion Gibb's energy between the sludge colloids but cannot be determined from a single shear experiment. For many practical purposes, however, the quantity $K_m m_{\mathrm{a,max}}$ would be suitable for quantifying the relative mass of dispersed to total solids in the low solids domain.

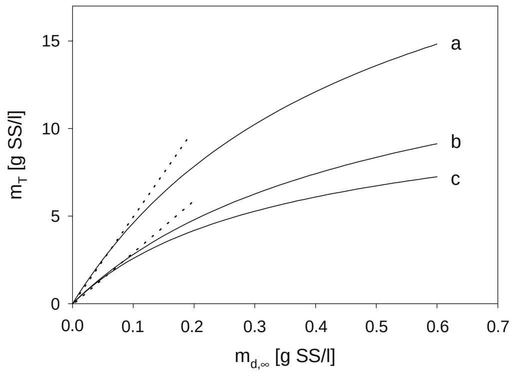

Fig. 1. Model calculations of $m_{\mathrm{d},\infty}$ versus m_T for combinations of K_m and $m_{\mathrm{a,max}}$. (a) $K_m = 2.2$ l/g SS, $m_{\mathrm{a,max}} = 25$ g SS/l, $K_m m_{\mathrm{a,max}} = 55$; (b) $K_m = 2.2$ l/g SS, $m_{\mathrm{a,max}} = 15$ g SS/l, $K_m m_{\mathrm{a,max}} = 33$; (c) $K_m = 3.3$ l/g SS, $m_{\mathrm{a,max}} = 10$ g SS/l, $K_m m_{\mathrm{a,max}} = 33$. The dotted lines indicate the initial slopes of $K_m m_{\mathrm{a,max}}$.

2.2. Shear effects

In the AE-model the impact of turbulent shear is treated in analogy to the effect of temperature on a molecular chemical equilibrium [23], an analogy suggested earlier by Reich and Vold [28] but not developed further. In general, when the kinetic energy (normally temperature) of a system is increased, this causes a shift in the equilibrium of a chemical reaction in the direction of the endothermic reaction. For example, increasing temperature causes increasing vapour pressure of a liquid. By analogy, increasing the turbulent energy in a suspension leads to increased kinetic energy of the suspension particles. For flocculent particles, erosion is an endothermic process, which in turn is favoured by the increase of turbulent energy. The analogy thus assumes that turbulence is the main cause of erosion of flocculated suspensions. This appears to be reasonable for particles of sizes larger than approximately 1 μm, since movement of these particles is caused by fluid motion rather than Brownian motion [7,28]. For a given total primary particle concentration the dispersed phase concentration in response to variations of shear is assumed to be governed by the enthalpy change of the adhesion [23]:

$$\ln m_{\mathrm{d},\infty} = \frac{\Delta H_G}{R}\frac{1}{G} + q_m, \tag{6}$$

where ΔH_G is the change of enthalpy by adhesion under the influence of turbulence, R is the gas constant, G is the root-mean-square velocity gradient developed by Camp and Stein [29]and q_m is a constant (the subscript m notifies the constant determined from mass concentration data; had a different unit been adopted for the dispersed phase concentration, this would be reflected in the value of q but would not affect $\Delta H_G/R$). From Eq. (6) follows:

$$m_{\mathrm{d},\infty} = \mathrm{e}^{(\Delta H_G/R)(1/G)}\,\mathrm{e}^{q_m}. \tag{7}$$

Since $\Delta H_G/R$ is negative [23] $m_{\mathrm{d},\infty}$ will approach 0 for $G \to 0$ and $m_{\mathrm{d},\infty} \to \mathrm{e}^{q_m}$ for $G \to \infty$. In Eq. (7), $\Delta H_G/R$ controls the sensitivity of $m_{\mathrm{d},\infty}$ to variations in G, while q_m determines the scaling of the dispersed phase concentration. Fig. 2 shows model calculations of

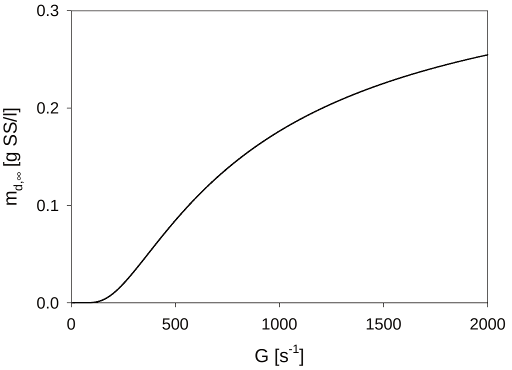

Fig. 2. Model calculations of $m_{d,\infty}$ versus G according to Eq. (6). $\Delta H_G/R = -735\,s^{-1}$, $q_m = -1.0$.

Eq. (7). The model predicts increasing dispersed phase concentration over the entire G-range, showing an S-shaped function with an inflection point. Thus, in erosion experiments equilibrium turbidity is not proportional to the turbulent shear rate in any range of shear. It is therefore not possible to obtain information on the shear dependence from a single experiment at some standardised shear rate, although this would have been desirable for many practical applications. The only means of characterising the shear dependence is therefore to use the theoretical model (Eq. (6)) to obtain estimates of $\Delta H_G/R$ and q_m. Experiments for more than one shear rate are required to obtain even rough estimates of these parameters. Therefore, for shear testing in a single experiment, a standardised shear rate must be chosen.

2.3. Shear characterisation

Camp and Stein [29] developed the root-mean-square velocity gradient (G) for characterisation of turbulent shear rates:

$$G = \sqrt{\frac{P}{\eta V}}, \tag{8}$$

where P is the power input, η is fluid viscosity and V is the suspension volume. The application of G to flocculation issues has been criticised by many researchers and adopted by even more. As pointed out by Cleasby [30], G is only valid when considering particles smaller than the Kolmogorov microscale (η_K) given by:

$$\eta_K = \sqrt{\frac{v}{G}}, \tag{9}$$

where η_K is the Kolmogorov microscale of turbulence and v is the dynamic viscosity.

Activated sludge primary particles are in most cases one or two orders of magnitude smaller than η_K. Therefore, they are dominated by viscous subrange effects, i.e. they are governed by dissipating energy, which is assumed independent of the flocs (although flocs will affect flow in the inertial subrange, all energy must ultimately dissipate). Hence, we assume that G is an appropriate parameter for turbulence characterisation when considering primary particle balances. This was supported experimentally also by the good fits obtained by Mikkelsen and Keiding [23].

3. Materials and methods

A series of shear tests were performed in order to investigate the effects of solids content, turbulent shear rate and paddle configuration on deflocculation behaviour.

3.1. Sludge

Activated sludge was collected from five wastewater treatment plants (Hirtshals, Marselisborg, Kjellerup, Horsens and Aalborg East), all treating combined industrial and domestic wastewater, and designed for advanced wastewater treatment with biological C- and N-removal and chemical P-removal. The plants are operated with a sludge age of approximately 30 days.

3.2. Shear reactor

In all tests a baffled reaction chamber was used, consisting of a 105 mm inner diameter cylinder with four vertical baffles each 11 mm deep. The reactor was placed in an iced water bath to ensure constant temperature (4°C) throughout the experiments. Paddles were placed centrally in the horizontal plane. A single bladed paddle $12 \times 50\,mm^2$ (heigth × width), placed ca. 4 cm above the bottom of the cylinder was used as standard paddle. Other paddles used in preliminary tests were a double bladed paddle, a turbine and a guarded propeller as depicted by Christensen [31]. The sludge volume was always 1000 ml at the initiation of experiments.

3.3. Solids content

Sludge was thickened to approximately 12–16 g SS/l and diluted with supernatant to 0.7–12 g SS/l. Following dilution, samples were stored overnight at 4°C with no shear before testing.

3.4. Shear rates

Turbulent shear rates (G) were calculated from Eq. (8). The power input was obtained through measurements of paddle shaft torque. Viscosity was estimated as that of pure water. Applied shear varied

Table 1
Paddle stirring speed [rpm] required for the applied G-values for the four paddles in a 1 l sample. The single bladed paddle was selected as standard

G (s^{-1})	Single bladed	Double bladed	Guarded	Turbine
500	670			
800	900	770	840	1000
1100	1150			
1400	1350			
1700	1560			

from $G = 500\text{–}1700\,s^{-1}$ with $800\,s^{-1}$ chosen as standard. The corresponding microscale of turbulence according to Eq. (9) was in the range 50–27 μm (for $G = 500$ and $1700\,s^{-1}$, respectively) with $\eta_K = 40\,\mu m$ for $G = 800\,s^{-1}$. Hence in all cases, primary particles (ca. 0.5–5 μm) were smaller than the microscale. Paddle speeds are listed in Table 1.

3.5. Shearing procedure

Sludge was sheared at pre-adjusted shear rates, and 5 ml samples for turbidity measurement were taken at shear durations of 0, 10, and 20 min and subsequently with 20 min intervals till 300 min. Decreasing sludge volume due to sampling increased the shear rate during experiments with <5% from start to finish.

3.6. Turbidity and dispersed mass concentration

Supernatant turbidity was measured following 2 min centrifugation at 3000 rpm (1000 × g). This was sufficient to ensure settling of flocs, and no effect was observed when supernatant was sonicated (data not shown), indicating that turbidity reflected dispersed primary particle concentrations. Turbidity (n_d) was measured as absorbance at 650 nm, and converted to formazine turbidity units (FTU) using a standard calibration curve. The turbidity to solids mass conversion factor of 1.2 mg SS/l/FTU as reported by Wahlberg et al. [18] was confirmed by initial experiments and adopted for estimating the dispersed mass concentration (m_d).

3.7. Fitting procedure

The work of Mikkelsen and Keiding [23] showed that the erosion kinetics could be fitted to the diffusion expression reported by Crank [32]:

$$m_{d,t} = m_{d,\infty} + (m_{d,0} - m_{d,\infty})\frac{6}{\pi^2}\sum_{N=1}^{9}\frac{1}{N^2}e^{-N^2Dt}, \qquad (10)$$

where $m_{d,t}$ is the dispersed mass concentration at time t, $m_{d,0}$ and $m_{d,\infty}$ is dispersed mass concentration initially and at equilibrium, respectively, N is an integer and D is an effective diffusion constant.

Data of dispersed mass concentration versus time were fitted to Eq. (10) using Sigma Plot non-linear regression, whereby estimates and standard deviations about these estimates were obtained for $m_{d,0}$, $m_{d,\infty}$ and D. To improve these estimates, data were refitted following the procedure described by Mikkelsen and Keiding [23], i.e. for varying solids content but constant shear ($G = 800\,s^{-1}$), the average D was calculated for each sludge, while for each solids content linear regression of D versus G was made. With these estimates of D, refitting of the measured data to Eq. (10) yielded improved estimates of $m_{d,0}$ and $m_{d,\infty}$.

Estimates of $m_{d,\infty}$ in response to variations of solids content or shear rate were fitted to the model Eqs (4) and (6), respectively.

4. Results

4.1. Effect of paddle configuration

Fig. 3 shows the measured dispersed mass concentration versus shear time for the four paddles operated with $G = 800\,s^{-1}$. From this figure no indications of systematic variation emerge. Fitting by Eq. (10) yielded no significant variations in the estimates of D or $m_{d,\infty}$. The average D of $1.21 \times 10^{-4}\,s^{-1}$ was adopted in refitting the data to Eq. (10). The new estimates of $m_{d,\infty}$ and $m_{d,0}$ are given in Table 2. No two estimates of $m_{d,\infty}$ were significantly different, and the standard deviation between estimates was only 4% of their mean. Thus, the four paddle configurations produce consistent degrees of erosion when operated with equal G. This confirms that the break-up process is due to turbulence

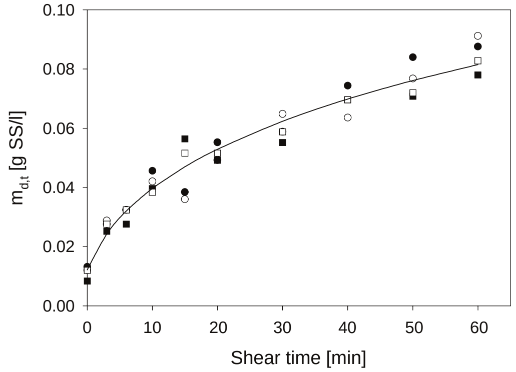

Fig. 3. Dispersed mass concentration versus shearing time for four different paddles operated with $G = 800\,s^{-1}$. The paddles were single bladed (○), double bladed (●), guarded (□), and turbine (■).

scales smaller than the Kolmogorov microscale, and thus G is suitable for quantification of the turbulent energy and can be applied for turbulence characterisation irrespective of paddle geometry.

4.2. Effects of solids content

Fig. 4 shows the effect of solids content on estimates of $m_{d,\infty}$ for the five sludges. The data for each sludge were fitted to Eq. (4) to obtain the estimates of $m_{a,\max}$ and K_m reported in Table 3.

Table 2
Fitting results and standard deviations ( ) according to Eq. (10) with $D = 1.21 \times 10^{-4}\,\text{s}^{-1}$ for four different paddles operated with $G = 800\,\text{s}^{-1}$. The solids content of the sludge was 3.72 g SS/l in all reactors

Paddle	$m_{d,\infty}$ (g SS/l)	$m_{d,0}$ (g SS/l)	R^2
Single bladed	0.146 (0.007)	0.012 (0.003)	0.963
Double bladed	0.140 (0.008)	0.011 (0.004)	0.944
Guarded	0.133 (0.006)	0.012 (0.003)	0.959
Turbine	0.134 (0.004)	0.014 (0.002)	0.987
Average	0.138 (0.006)	0.012 (0.001)	0.963
All data	0.138 (0.003)	0.012 (0.002)	0.957

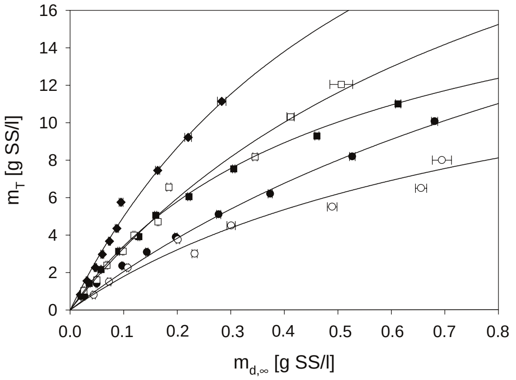

Fig. 4. Estimates of $m_{d,\infty}$ versus solids content for five sludges: Hirtshals (◆), Marselisborg (□), Horsens (■), Aalborg East (●) and Kjellerup (○). The shear rate was $G = 800\,\text{s}^{-1}$.

The product $K_m m_{a,\max}$ controls the stability for low solids contents, e.g. the Hirtshals sludge has the largest $K_m m_{a,\max}$ and thus the lowest turbidity relative to solids content. Marselisborg and Kjellerup sludges were estimated to have similar K_m but show different stabilities in the low solids domain due to different $m_{a,\max}$. As the solids content is increased all sludges show a higher turbidity per solids mass (i.e. a higher dispersed to total mass ratio). This becomes increasingly pronounced as the solids content of a sludge approaches $m_{a,\max}$. The estimates of $m_{a,\max}$ differ by more than a factor 2 between the sludges. Therefore, the turbidity versus solids content curves sometimes cross at some solids content. As an example the Horsens sludge has a relatively large K_m and the stability is similar to the Marselisborg sludge for low solids contents. As the solids content is increased, however, the low $m_{a,\max}$ of the Horsens sludges causes increased dispersion relative to the Marselisborg sludge, and for solids contents above approximately 14 g SS/l the Horsens sludge becomes more dispersed than the Aalborg East sludge, in spite of the much lower K_m of the latter.

Fig. 4 indicates a close to linear relation between the equilibrium dispersed mass concentration ($m_{d,\infty}$) and solids content (m_T) for solids contents lower than approximately 4 g SS/l. This value was used as a limiting solids content (SS_L) to asses the feasibility of standardising the solids content for a simplified shear test based on only a single shear experiment. According to Eq. (5) $m_{d,\infty}/m_T$ may be assumed equal to $1/(1 + K_m m_{a,\max})$ for low solids contents. For each of the five sludges $m_{d,\infty}/m_T$ was calculated from a single experiment with solids content in the range 3.5–4.0 g SS/l and compared with the estimates of $1/(1 + K_m m_{a,\max})$ based on the entire solids range experiments. There was a fair correlation ($R^2 = 0.965$) as shown also in Fig. 5. The slope was 1.130 ± 0.035, indicating a slight overestimation of $1/(1 + K_m m_{a,\max})$ from the single experiments. Model calculations from Eq. (4) of $m_{d,\infty}/m_T$ for $m_T = 4$ g SS/l and $m_T \to 0$, respectively, showed that for the values of $m_{a,\max}$ reported herein a 14–33%

Table 3
Results and standard deviations ( ) from fitting to Eq. (4) for five sludges with $G = 800\,\text{s}^{-1}$. Estimates of $k_{SS} = m_{d,\infty}/m_T$ were obtained from experiments with the reported solids contents (m_T), all in the range 3.5–4.0 g SS/l

Sludge	K_m (l/g SS)	$m_{a,\max}$ (g SS/l)	$K_m m_{a,\max}$ [dimensionless]	R^2	m_T (g SS/l)	$k_{SS} = m_{d,\infty}/m_T$ [dimensionless]
Hirtshals	1.80 (0.46)	32.2 (6.2)	57.9	0.989	3.67	0.0200 (0.0006)
Marselisborg	1.24 (0.36)	29.0 (5.8)	36.1	0.984	3.99	0.0299 (0.0005)
Kjellerup	1.37 (0.36)	13.8 (2.0)	18.8	0.974	3.75	0.0536 (0.0008)
Horsens	2.25 (0.13)	17.7 (0.6)	39.8	0.999	3.91	0.0329 (0.0005)
Aalborg East	0.81 (0.11)	26.4 (2.4)	21.4	0.998	3.89	0.0508 (0.0006)

(average of 20% ± 8%) increase of $m_{d,\infty}/m_T$ should be expected as the solids content is increased from 0 to 4 g SS/l. Thus, the observed slope is within the theoretically expected range. It seems that for comparative purposes estimates of $m_{d,\infty}/m_T$ for $m_T = 3.5-4.0$ g SS/l may be valuable as an indicator of $K_m m_{a,\max}$. In all cases $K_m m_{a,\max} \ll 1$, so that a close to inverse relation between $m_{d,\infty}/m_T$ and $K_m m_{a,\max}$ should be expected, i.e. $m_T/m_{d,\infty} \approx K_m m_{a,\max}$. Linear regression of this relation resulted in the expression $m_T/m_{d,\infty} = (0.86 \pm 0.03) \cdot K_m m_{a,\max}$ with $R^2 = 0.957$.

4.3. Effects of shear

For each sludge the data for $m_{d,\infty}$ from erosion at different shear rates were fitted to Eq. (6). The resulting estimates of $\Delta H_G/R$ and q_m are given in Table 4. Some typical examples of the impact of shear on $m_{d,\infty}$ are shown in Fig. 6, showing a large impact in the shear range of the present investigation, in particular for shear rates up to $G \approx 1100\,\mathrm{s}^{-1}$. The model predicts the existence of a region of almost complete incorporation of primary particles in flocs in the low shear domain, i.e. below $G \approx 160\,\mathrm{s}^{-1}$. This point is not apparent from the data shown in Fig. 6, but was confirmed in subsequent shear tests. Thus, turbidity is expected to be relatively unaffected by increments of shear in the range $G \approx 0-160\,\mathrm{s}^{-1}$ as well as for very large shear rates. A standard shear rate of $G = 800\,\mathrm{s}^{-1}$ takes a fairly central position in the typical shear range of predominant erosion.

5. Discussion

The AE-model developed by Mikkelsen and Keiding [23] provided good fits to the equilibrium dispersed mass concentration data obtained for five different activated sludges. The model implies increasing dispersion with

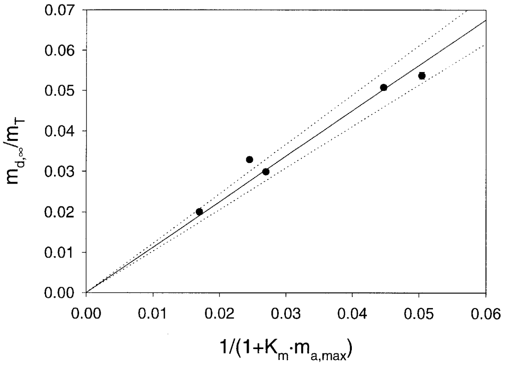

Fig. 5. Estimates of $m_{d,\infty}/m_T$ for experiments with solids content in the range 3.5–4.0 g SS/l versus $1/(1+K_m m_{a,\max})$. Linear regression results ($R^2 = 0.965$) with the 95% confidence interval are shown.

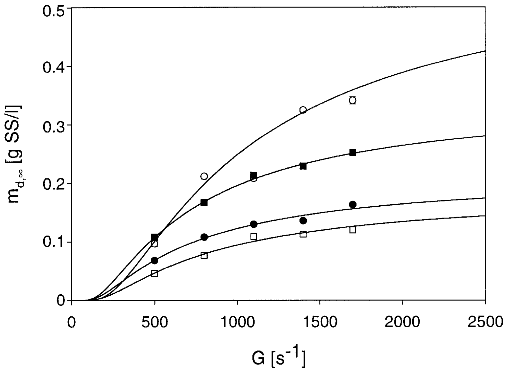

Fig. 6. Estimates of $m_{d,\infty}$ versus shear for Kjellerup sludge with $m_T = 3.47$ g SS/l (○), Aalborg East sludge with $m_T = 2.44$ g SS/l (●) and Horsens sludge with $m_T = 3.68$ g SS/l (□) and $m_T = 5.89$ g SS/l (■). The lines show results of fitting to Eq. (6).

Table 4
Fitting results and standard deviations ( ) from Eq. (6)

Sludge	m_T (g SS/l)	$\Delta H_G/R$ (s^{-1})	q_m	e^{q_m} (g SS/l)	R^2
Hirtshals	3.22 (0.05)	−765 (19)	−1.401 (0.022)	0.246	0.998
	5.33 (0.10)	−599 (26)	−1.024 (0.029)	0.359	0.996
Marselisborg	3.35 (0.05)	−725 (71)	−1.284 (0.081)	0.277	0.972
	5.30 (0.04)	−557 (62)	−0.891 (0.070)	0.410	0.964
Kjellerup	3.47 (0.07)	−901 (57)	−0.496 (0.064)	0.609	0.992
	5.73 (0.07)	−716 (107)	0.042 (0.054)	1.043	0.957
Horsens	3.68 (0.11)	−701 (52)	−1.663 (0.059)	0.190	0.984
	5.89 (0.09)	−597 (19)	−1.031 (0.021)	0.357	0.997
Aalborg East	2.44 (0.02)	−584 (41)	−1.514 (0.046)	0.220	0.986
	4.84 (0.03)	−526 (27)	−0.695 (0.031)	0.499	0.992

increasing solids content, i.e. erosion increases relative to adhesion when solids content is increased. This is contradictory to the usual expectation that increasing solids content causes increasing probability of particle collisions, hence leading to higher rates of flocculation as well as providing a larger surface for erosion as argued by Parker et al. [8], who therefore expected the dispersed mass concentration to be independent from the total solids content.

The experiments showed that shear effects on equilibrium dispersion may be described by Eq. (6), which adopts G for characterisation of shear rates. The convincing fit of data to the AE-model as well as the insignificance of paddle configuration have confirmed the appropriateness of G for studies of primary particle erosion in activated sludge. This is fortunate with respect to methods for characterisation of interaction energies between colloids. It is, however, of prime importance also for the interpretation of shear test results with implications for solid/liquid separation processes. Thus, by determining G and residence time in various parts of a treatment plant, there is a potential for transfer of laboratory test data to the full-scale operation of wastewater treatment plants.

Estimates of $m_{\mathrm{d},\infty}/m_{\mathrm{T}}$ from experiments with m_{T} of 3.5–4.0 g SS/l showed a fair correlation to $1/(1+K_m m_{\mathrm{a,max}})$ as predicted theoretically by Eq. (5). It is therefore suggested that the stability of aggregated colloid suspensions may be characterised by a shear sensitivity parameter defined from a shear test with $m_{\mathrm{T}} \leqslant \mathrm{SS_L}$ (typically ca. 3.5–4.0 g SS/l) and $G = 800\,\mathrm{s}^{-1}$ as:

$$k_{\mathrm{SS}} = \frac{m_{\mathrm{d},\infty}}{m_{\mathrm{T}}} \approx \frac{1}{1+K_m m_{\mathrm{a,max}}}, \tag{11}$$

where k_{SS} is the shear sensitivity constant. The parameter k_{SS} predicts the equilibrium dispersion ratio of a given sludge when exposed to a fixed turbulent shear rate ($G = 800\,\mathrm{s}^{-1}$) and present at solids content $m_{\mathrm{T}} \leqslant \mathrm{SS_L}$. The parameter is named as the "shear sensitivity", as opposed to the term floc strength that has been adopted in past research (e.g. [33,22]). This is due to two reasons: (1) The parameter does not quantify the strength but rather the sensitivity in terms of the tendency for erosion, as increasing k_{SS} leads to increasing dispersion, i.e. the parameter provides information on how sensitive the sludge is to shear with respect to release of primary particles. (2) From the parameter we do not make inferences about the state of the floc, but focus on the primary particles; hence the term floc in inappropriate in this context. It follows from Eq. (11) that k_{SS} is dimensionless, or it can be expressed as a percentage.

Eq. (11) is only valid for low solids contents ($m_{\mathrm{T}} \leqslant \mathrm{SS_L}$). On the other hand, the relative error in measured turbidities is larger for low turbidities. Therefore, it is ideal to use $m_{\mathrm{T}} = \mathrm{SS_L}$. The relative error in estimates of $m_{\mathrm{d},\infty}$ decreases with increasing shear rate. For standardisation purposes a solids content of 3.5–4.0 g SS/l and a shear of $G = 800\,\mathrm{s}^{-1}$ is therefore suggested. However, $\mathrm{SS_L}$ is unique to each sludge and therefore, ideally, should be tested for.

As $k_{\mathrm{SS}} \approx 1/(1+K_m m_{\mathrm{a,max}})$ and $K_m m_{\mathrm{a},max} \leqslant 1$ it follows that $k_{\mathrm{SS}} \approx 1/K_m m_{\mathrm{a,max}}$. Thus, k_{SS} decreases with increase of both K_m and $m_{\mathrm{a,max}}$. Therefore, the greater the affinity of adhesion (governed by the interaction energy) and the greater the maximum level of adhesion, the lower would be the equilibrium dispersed mass concentration for given shear rate and solids content. K_m and $m_{\mathrm{a,max}}$ seem to be independent ($R^2 = 0.052$), and it is not possible to distinguish between changes in K_{m} and $m_{\mathrm{a,max}}$ from determinations of k_{SS}. Such deduction would require a series of experiments fitted to Eq. (4) as described by Mikkelsen and Keiding [23]. For many practical purposes, however, k_{SS} may provide a good indication of the colloidal properties of a sludge. It must be remembered though, that predictions of dispersion levels beyond $\mathrm{SS_L}$ should be considered with great care, or preferably not made at all. For such purposes the full model described in Mikkelsen and Keiding [23] should be used, i.e. Eqs. (4) and (6). However, the apparent viscosity of activated sludge increases with solids content in the same manner as $m_{\mathrm{d},\infty}$ [34]. Therfore, combination of shear testing and viscosity measurements would make modelling of solids effects on dispersion possible over a greater solids range.

The shear sensitivity k_{SS} gives a characterisation of the chemical equilibrium of the system as determined by the energetically most favourable condition in a thermodynamic sense. According to general thermodynamics any system will tend towards decreasing entropy, i.e. a higher degree of dispersion, due to the kinetic energy of the system. However, this is opposed by some degree of attraction between the reacting species. Hence, the result is some intermediate state, where the degree of dispersion is determined by the relative magnitude of kinetic energy to potential energy of interaction. Drawing a parallel to shear testing of activated sludge, it seems reasonable that increasing the kinetic energy through turbulent shear increases the dispersion level, while the potential interaction energy of the sludge particles determine the extent to which the erosion may proceed. Hence, there is reason to believe that k_{SS}, given from the dispersed mass concentration $m_{\mathrm{d},\infty}$ relative to the solids content in a standardised shear test procedure, provides a meaningful characteristic of the surface chemical state of the sludge particles, i.e. it gives a measure of the interaction energy. It was suggested earlier by Gregory [7] that deductions of interaction energies may be based on the equilibrium concept as applied in this study, when dispersed and flocculated phases co-exist. This was mainly based on the work of Long et al. [26], in which the dispersed concentration of latex particles could be related to calculated interaction potentials. By use of the AE-model, it seems that such characterisation of colloid interactions is possible in a flocculated system as e.g. activated sludge, when adhesion and erosion are the determining mechanisms of flocculation and break-up, respectively.

6. Conclusions

The quantity of dispersed primary particles in activated sludge as a function of solids content and turbulent shear rate may be approached by the AE-model of Mikkelsen and Keiding [23]. As the dependency of primary particle concentration upon both solids content and shear rate is non-linear, it is not possible to quantify these relationships in only one parameter. When, however, for practicality, a simplified test is required, a standardised shear test is suggested, which quantifies the shear sensitivity k_{SS}.

The shear sensitivity k_{SS} quantifies the adhesion–erosion balance in terms of the equilibrium degree of dispersion of sludge at low solids content and fixed turbulent shear rate standardised at $G = 800\,s^{-1}$.

The parameter k_{SS} is convenient, as it requires only one shear test procedure. However, its weakness lies in the fact that we cannot separate effects of changed interaction energy (via K_m) and changed maximum degree of primary particle incorporation into flocs ($m_{a,max}$) Thus, when $m_{a,max}$ differs between two sludges of equal k_{SS}, they will not be equally dispersed for high solids content, and the interaction energies between the colloids will not be identical. For scientific research such problems should be considered carefully. As an engineering parameter, k_{SS} is convenient for quantification of the affinity of adhesion–erosion, when the degree of dispersion is critical.

More work is needed to relate the surface chemistry of biological colloids to their interaction energies. This will be the issue of future publications. Mikkelsen and Nielsen [35] and Mikkelsen [34] address the potential use of k_{SS} for deduction of changes in interaction energy. The latter paper provides a discussion of the links between bond strength characterisation methods based on turbidity, filterability and the slope of these parameters versus time as adopted in past research.

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