Effects of solids concentration on activated sludge deflocculation, conditioning and dewatering

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Abstract Optimum conditioning of activated sludge in terms of minimum CST was shown to correspond to the complete removal of turbidity, and the increase in turbidity with shear due to e.g. pumping is therefore expected to affect conditioning. The optimum polymer dosage was directly related to the turbidity of activated sludge after two minutes shear, and was considerably lower than the dosage required for charge neutralisation. The turbidity produced by shear increased more than is proportional with solids concentration and was directly related to the apparent viscosity. It is suggested that increasing solids concentration causes increased surface erosion when network structures are broken, and this causes increases in turbidity and required polymer dosage per solids mass. For Åby activated sludge, optimum polymer dosage per solids mass increased by 52% when the solids concentration was increased from 8.2 to 13.7 g SS/l. Modelling of the effect of solids concentration predicts even higher increases in required polymer dosage for higher solids concentrations. This means that reduced thickening prior to pumping and conditioning may be desirable when the hydraulic capacity of the dewatering device is sufficient. Similar trends were observed for an anaerobically digested sludge. For this sludge, reduction of turbidity with $FeCl_3$ reduced the polymer demand.

Keywords Deflocculation; dewatering; floc strength; polymer dosage; rheology; shear sensitivity; viscosity

Introduction

Dewatering of waste activated or digested sludge is a costly business in the running of wastewater treatment plants. Expenses related to the dewatering step, including conditioning agents, typically account for 30-50% of the annual operating costs of municipal treatment plants (Sørensen, 1996). Dewatering is typically achieved by use of filter presses or centrifuges following thickening, pumping and conditioning of the waste sludge. Considering the large costs related to the dewatering step it seems highly relevant to improve our understanding of the relation between suspension structure and dewaterability, and in particular how to control suspension structure for optimisation of conditioning and dewatering.

The importance of particle size distribution in solid/liquid separation has been stressed by many researchers, e.g. Tadros and Mayes (1979), Moudgil and Scheiner (1988). Fines (micrometre-sized colloidal particles) in particular are difficult to separate. In separation by centrifuge, solids recovery decreases with increasing fines content (Spinosa and Minimmi, 1984), while in filtration they produce filter cakes of low permeability (Akers and Machin, 1979). Decreased filterability with increasing colloidal content in terms of supernatant turbidity has been reported with respect to both capillary suction time (CST) (Eriksson *et al.*, 1988; King and Forster, 1990) and specific resistance to filtration (SRF) (Wu *et al.*, 1985; Lawler *et al.*, 19886; Rasmussen *et al.*, 1994). Optimum dosage of conditioning agents has also been reported to increase with the fraction of colloids (Busch and Stumm, 1968; Wu *et al.*, 1985; Eriksson, 1987).

The particle size distribution of activated sludge is bimodal (Parker *et al.*, 1971; Li and Ganczarcyk, 1991) with fines corresponding to dispersed single bacteria sized around 0.5-5 µm. The larger sized particles are flocs, which contain single bacteria and bacterial

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colonies held together in a matrix of extracellular polymers (Jorand *et al.*, 1995; Nielsen and Keiding, 1998). The fraction of fines depends on the origin of the sludge (Mikkelsen and Keiding, submitted), bacterial growth conditions (Wu *et al.*, 1985), the chemical environment as e.g. salt concentration (Zita and Hermansson, 1994), and turbulent shear forces (Parker *et al.*, 1971; Das *et al.*, 1993). The strength of flocs in terms of ability to resist production of fines by erosion is therefore considered important for dewatering by filtration or centrifugation. The binding strength (or interaction energy) of single bacteria to floc surfaces may be regarded as a colloid chemical phenomenon, whereby the adhesion force decreases with e.g. increased electrostatic repulsion (Zita and Hermansson, 1994; Mikkelsen *et al.*, 1996). According to general DLVO theory, van der Waals forces and electrostatic forces affect inter-particle attraction, as do non-DLVO forces as hydrophobic interaction, steric forces, and polymer entanglement (Unz, 1987). These forces upon addition, determine the interaction energy between the sludge particles. The interaction energy in turn is expected to govern the fraction of fines present in a sludge, as quantified by the shear sensitivity (Mikkelsen, 1999; Mikkelsen and Keiding, submitted).

It was recently shown, that the colloidal fraction of a suspension with given interaction energy increases with increases in either solids concentration or turbulent shear (Mikkelsen and Keiding, 1999). In order to control the amount of fines in a suspension it is therefore important to consider these factors also. A semi-theoretical model expression for the colloid concentration for varying solids concentration and fixed turbulent shear (G) was developed by Mikkelsen and Keiding (1999, submitted):

$$m_T = m_d + \frac{m_{a,\max} \cdot K_m \cdot m_d}{1 + K_m \cdot m_d} \tag{1}$$

where m_T is the total solids mass concentration, m_{d} is the dispersed mass concentration (colloid content), $m_{\mathrm{a,max}}$ is the maximum solids mass that may be incorporated into flocs, and K_{m} is the equilibrium constant (reflecting the interaction energy or binding strength between the particles).

For a given solids concentration the effect of shear on colloid concentration was modelled as (Mikkelsen and Keiding, submitted; Mikkelsen, 1999):

$$m_d = \exp(\Delta H_G / G)\ \exp(q_m) \tag{2}$$

where ΔH_{G} is the change of enthalpy by turbulent shear, G is the root-mean-square velocity gradient by Camp and Stein (1943) for characterisation of turbulent shear, and q_{m} is a constant for a given solids concentration.

Equations 1 and 2 imply increased colloidal fractions of a suspension with increases in either solids concentration or turbulent shear (the latter follows as ΔH_{G} is negative). This in turn is expected to cause increased optimum polymer dosage for conditioning as well as increased resistance to filtration and decreased solids recovery in centrifugation. The aim of the present study was therefore to investigate effects of sludge solids concentration on dewatering by filtration. Effects of solids concentration on SRF and optimum polymer dosage were investigated and related to the production and removal of colloids due to shear and conditioning, respectively. The production of colloids was further related to sludge rheology.

Materials and methods

Activated sludge from Åby wastewater treatment plant was used for the experiments. The plant performs advanced treatment with N- and P-removal. The sludge age was approximately 30 days. The sludge was thickened to 17.2 g SS/l and diluted with sludge supernatant to different solids concentrations.

Optimum conditioner dosage was estimated by addition of polymer (0.5% Zetag 57) following two minutes shearing (G = 1200 s^{-1}). The polymer was added and mixed in the sludge under turbulent shearing with G=800 s^{-1} for 30 seconds, followed by 30 seconds flocculation with G=120 s^{-1}. Following this procedure, turbidity and CST were measured. The procedure was repeated for different polymer doses, and the optimum dosage determined as that required to achieve minimum CST and residual turbidity.

Turbidity was measured as absorbance (650 nm) of supernatant after two minutes centrifugation at 2200 rpm. The absorbance was converted to Formazine turbidity Units (FTU) by a standard calibration curve. Dispersed mass concentrations were estimated by use of the turbidity to mass concentration conversion factor of 1.2 mg SS/l/FTU reported by Wahlberg (1992).

Specific resistance to filtration (SRF) was estimated by filtering of 200 ml sludge samples through a 5 cm diameter Whatman#41 filter with an applied pressure of 1 bar. Filtrate volume was recorded versus time, and SRF was estimated from plots of dt/dV against V according to the equation by Sorensen *et al.* (1995):

$$\frac{dt}{dV} = \frac{\mu}{P}\left(SRF \cdot C \cdot V + R_m\right) \tag{3}$$

where t is filtration time, V is filtrate volume per unit cross-sectional area, μ is the filtrate viscosity, P is the applied pressure, C is the deposited total mass of solids per unit filtrate volume and R_m is the medium resistance. From a dt/dV versus V plot, the slope (α) and intercept (α_0) correspond to the first and second terms in eq. 3, respectively (α-$SRF \cdot C \cdot \mu/P$; $\alpha_0 = R_m \cdot \mu/P$).

Apparent viscosity (μ_α) of sludge was measured with a Brookfield digital viscometer model LVTDT-II operated at a shear rate of 7.34 s^{-1}. Readings were made also with a shear rate of 3.67 s^{-1} and the Bingham yield stress (τ_B) was estimated by extrapolation of stress shear rate data from the two measurements.

The zeta-potential of conditioned sludge was measured with a Malvern Zetamaster. Immediately prior to measurement, 1 ml conditioned sludge was diluted to 100 ml with deionised water. Average floc size of conditioned sludge was measured with a Microtrack particle sizer.

Results

Waste activated sludge is typically thickened and stored for different lengths of time before the dewatering process. When a dewatering cycle is initiated, sludge is pumped from the storage tank and conditioned with organic polymers just prior to entering the dewatering equipment (typically a filter press or centrifuge). In this procedure, the thickened sludge is

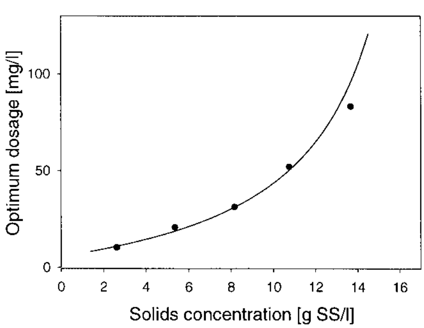

Figure 1 Optimum polymer dosage for different activated sludge concentrations

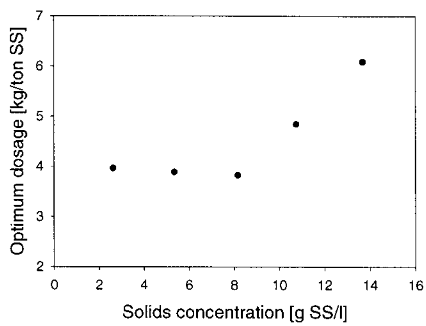

Figure 2 Optimum polymer dosage per solids mass for different activated sludge concentrations

exposed to shear forces in the pump and pipe system. Thus, some deflocculation may arise prior to the addition of conditioner, and this may affect the required conditioner dosage. To investigate this effect, a series of experiments was performed in which activated sludge of different solids concentration was exposed to turbulent shear (G=1200 s^{-1}) for two minutes prior to addition of polymer. The optimum polymer dosage was determined as the dosage required for minimum CST and supernatant turbidity.

The optimum polymer dosage increased with the activated sludge solids concentration both in terms of absolute dosage (Figure 1) and dosage per solids content for solids concentrations above approximately 8 g SS/l (Figure 2). Optimum dosage per solids mass was increased by 52% when the solids concentration was increased from 8.2 to 13.7 g SS/l.

Optimum polymer dosage did not correspond to charge neutralisation of the activated sludge. The zeta potential at optimum conditioner dosage was -18±3 mV. When over-conditioned (in terms of increasing CST), the zeta potential remained negative even for doses up to four times the optimum polymer dosage. The dosage required to obtain charge neutralisation was not quantified.

Supernatant turbidity prior to conditioning also increased with solids concentration as shown in Figure 3. Comparison of Figures 1 and 3 indicates similar dependencies on solids concentration for the colloid concentration and the polymer dosage required for optimum flocculation. This is illustrated by the correlation (R^2=0.91) between the supernatant turbidity and the optimum dosage as seen in Figure 4.

Figure 5 shows the apparent viscosity estimated with a viscometer shear rate of 7.34 s^{-1} versus solids concentration. Again, a more than proportional increase with solids concentration was seen in the high solids range. As in the study of Mikkelsen (submitted) the apparent viscosity at the fixed shear rate correlated with the Bingham yield stress τ_B (R^2=0.98). Comparing Figures 3 and 5 suggests that the increase of turbidity with solids concentration may be a consequence of increased surface erosion caused by break-up of inter-particle structures, as reflected by the apparent viscosity and yield stress. Thus assuming a link between μ_a and turbidity, it is possible to fit data of μ_a versus solids concentration to eq. 1 modified by replacing μ_d with $\mu_a \bullet k$, where k is an (unknown) proportionality factor as described by Mikkelsen (submitted). This provided a good fit (R^2=0.98) with an estimate of $m_{a,max}$=18.6 g SS/l. The model fit is shown in Figure 5. The estimate of $m_{a,max}$ allows for the calculation of turbidity and optimum polymer dosage as a function of suspended solids concentration. These calculations are shown in Figures 1 and 3, respectively.

Filtration experiments for sludge of different solids concentrations were carried out with a fixed ratio of conditioner to solids content, corresponding to the optimum dosage (4.0 mg/g SS) in the low solids domain (i.e. solids content less than approximately 8 g SS/l

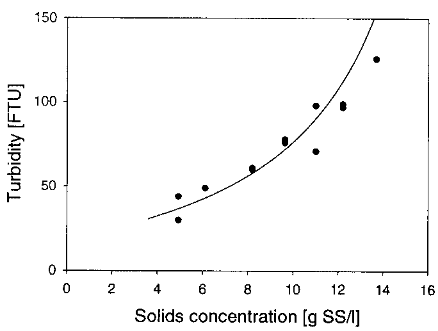

Figure 3 Supernatant turbidity prior to conditioning for different activated sludge concentrations

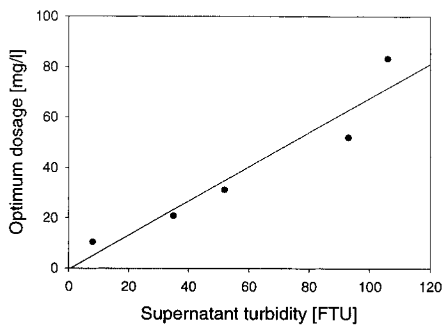

Figure 4 Correlation between supernatant turbidity before conditioning and optimum polymer dosage (R^2=0.91). The slope was 6.8 $\times 10^{-4}$ g/l/FTU, corresponding to 0.57 g Zetag 57 per g dispersed mass.

as seen in Figure 2). The sludges were exposed to a shear of G=1200 s^{-1} for two minutes and conditioned with the fixed conditioner dosage. A 30 second flocculation period with G=120 s^{-1} was allowed before measurement of residual turbidity and filtration characteristics.

Figure 6 shows the supernatant turbidity after conditioning with the fixed ratio of Zetag 57 to solids mass. The data indicate almost complete removal of colloidal matter for solids concentrations less than approximately 7 g SS/l, but increasing residual turbidity for higher solids concentrations. This in turn is reflected by the more than linear increase of α (slope of dt/dV versus V in the filtration plot) with solids concentration in the domain above 7 g SS/l (Figure 7). In Figure 7 the model fit was obtained from fitting to e.g. 1 with m_d substituted with $\alpha = k_1 \cdot m_d + k_2$, where k_1 and k_2 are constants. Disregarding the constant term, which may be due to medium blinding, the cake contribution to SRF is shown in Figure 8. The cake resistance increases for solids concentration above approximately 7 g SS/l due to the increased α. This was not due to differences in floc size, as there were no tendencies of variation in floc size with solids concentration. The average floc size following conditioning was 131±19 μm.

The same general trends as described above were observed for an anerobically digested sludge from the same treatment plant. The optimum ratio of polymer (Zetag 75) to solid mass was found to increase for solids concentrations above a certain value, in this case above approximately 10 g SS/l (Figure 9). As for the activated sludge, this again corresponded to the solids concentration above which the apparent viscosity increased more than proportional to the solids concentration. The reduction in polymer to solids mass was 22% when solids concentration was reduced from 17.2 to 6.3 g SS/l.

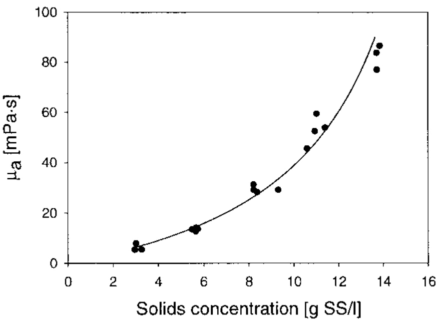

Figure 5 Apparent viscosity for different activated sludge concentrations

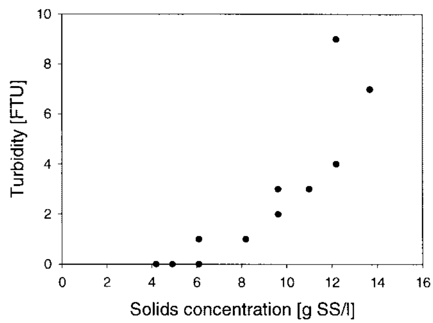

Figure 6 Residual turbidity after Zetag 57 conditioning with 4.0 mg/g SS for different activated sludge concentrations

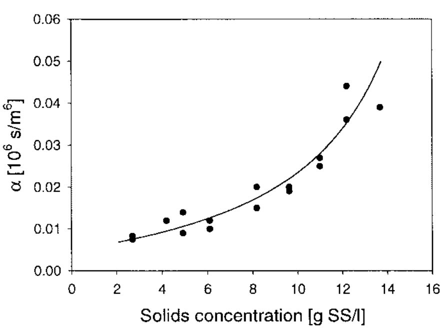

Figure 7 Filtration plot slope (α) for different activated sludge concentrations conditioned with Zetag 57 (4.0 mg/g SS)

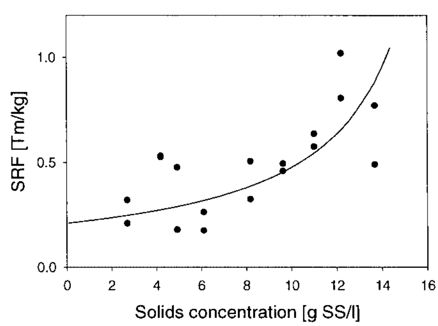

Figure 8 Cake specific resistance to filtration for different activated sludge concentrations conditioned with 4.0 mg/g SS of Zetag 57

The optimum polymer dosage per solids concentration was high for the anaerobic sludge compared to the activated sludge. This could be a reflection of the very large colloidal fraction (indicated by a large turbidity) of the anaerobic sludge. This was supported by the finding that a substantial decrease in polymer dosage was possible when turbidity was reduced by pre-conditioning with $FeCl_3$. This effect was however, not studied in detail in the present work.

Discussion

The present study shows strong indications that the dosage of conditioning agents required for optimum dewatering corresponds to removal of colloidal material from the dispersed phase. For activated sludge, complete removal of turbidity was possible at optimum dosage, but increased polymer doses per solids mass were required for high solids concentrations, when the turbidity per solids mass was increased in response to the two minutes shear procedure. The optimum polymer dosage for a given sludge was directly correlated to the turbidity at the point of conditioning. This correlation means that the model presented in eq. 1 can be utilised for model calculations of both the dispersed mass concentration and optimum conditioner dosage.

Charge neutralisation on the other hand did not correspond to optimum dosage, as the zeta potential remained negative even for considerable over-dosing, a finding in agreement with the work of Tyagi and Bowen (1989) in which residual negative surface changes were studied by means of microscopic examination. Erikkson (1987) also found no correlation between electrophoretic mobility and conditioner dosage, while Busch and Stumm (1968) commented that charge neutralisation is not necessarily a requirement for flocculation. We suggest that reduction of the colloid fraction is a critical factor in dewatering and not necessarily coincident with charge neutralisation.

The reason behind the increasing turbidity with increased solids concentration may be related to sludge rheology. Similar to the finding of Mikkelsen (submitted) the present data indicated correlations between the Bingham yield stress (τ_B), apparent viscosity (μ_a) at a fixed shear rate of measurement, and the turbidity in response to a fixed shear procedure. Increase of τ_B indicates the development of increased numbers of inter-particle contacts when the solids concentration is increased, leading to a higher shear stress required to break those contacts in order to allow liquid flow (Lang and Rha, 1980). The increase of turbidity with solids concentration is therefore interpreted as a result of increasing surface erosion due to the increased inter-particle network as argued by Mikkelsen (submitted) and Mikkelsen (1999).

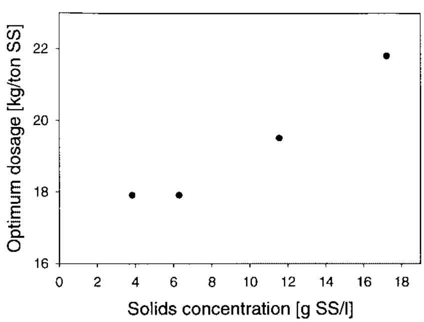

Figure 9 Optimum polymer dosage (Zetag 75) for different concentrations of a thermophilic anaerobically digested sludge

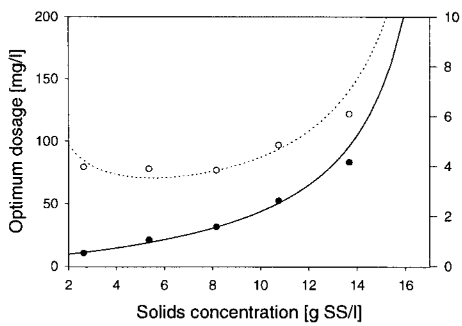

Figure 10 Model calculation of the polymer demand in response to solids concentration for Åby activated sludge with $m_{a,max}$=18.6 g SS/l. (•): dosage per volume; (°): dosage per solids mass.

When the conditioner dosage is proportional to the dispersed mass concentration, it is useful to adopt eqs. 1 and 2 for sludge characterisation and process optimisation. Once the sludge parameters K_m, $m_{a,max}$ and ΔH_G are known, the effect of solids concentration and shear on polymer requirement may be established. For example, extensive thickening of sludge prior to dewatering may not necessarily be advantageous to the dewatering process. It has normally been assumed that reduction of the hydraulic loading of the dewatering equipment by means of thickening is desirable. However, the present work indicates that when sludge is thickened to concentrations approaching $m_{a,max}$, we should expect the turbidity per solids mass (after pumping to the dewatering device) and optimum polymer dosage per solids mass to be higher than if the sludge had been thickened less or not at all. This is illustrated by model calculations in Figure 10. This means that polymer cost per solids mass is higher than possible for a lower solids concentration, or alternatively that the dewatering process is less efficient due to under-conditioning. The consequence is expected to be higher specific resistance to filtration and lower solids recovery in centrifugation. Therefore, in order to maintain the lowest possible optimum polymer dosage as well as optimum dewaterability, it may be beneficial to keep solids concentrations below some limiting concentration, above which the turbidity per solids mass increases rapidly. The limiting solids concentration may be estimated from measurements of turbidity or CST in a shear test, or by apparent viscosity readings in response to variations in solids concentration. Avoiding excessive thickening is expected to be beneficial in particular to centrifuge dewatering, as the hydraulic capacity of centrifuges is usually not limiting to the process (Hagström, 1999). With respect to filtration, increasing the hydraulic load may be problematic. Decanting supernatant after conditioning may possibly solve this.

Eq. 1 states that the interaction energy between sludge particles (related to K_m) affects the degree of dispersion for given solids concentration and shear, and the interaction energy is therefore an important parameter in sludge conditioning. The shear sensitivity parameter (k_{SS}) was defined by Mikkelsen and Keiding (submitted) and Mikkelsen (1999) as the ratio of equilibrium dispersed mass concentration relative to the total solids concentration, estimated from a shear test with G=800 s^{-1} and solids concentration 3.5-4.0 g SS/l, i.e. lower than the limiting solids concentration. As this parameter by definition quantifies the colloid to solids mass ratio, it is expected also to be related to the optimum polymer demand for a given treatment plant (i.e. fixed pump configuration) for solids concentrations lower than the limiting value.

Characterisation of shear sensitivity as a monitoring parameter thus seems relevant to the operation of dewatering processes. It is likely also, that full characterisation of sludge (in terms of estimating K_m, $m_{a,max}$ and ΔH_G) has potential use for prediction of the changes in polymer demand upon changes of both shear levels and solids concentrations caused by changes in e.g. pumping systems or the extent of thickening prior to dewatering. This is so, because once these parameters are known, eqs. 1 and 2 predict the colloid mass concentration (m_d) in response to variations of solids concentration and shear, respectively, and the polymer demand is expected to be directly related to m_d.

Conclusions

Based on the present study it was concluded that optimum polymer dosage for conditioning is directly related to the fraction of fines in the sludge. Thus, as the turbidity to solids concentration ratio increases with increasing solids concentration, so does the optimum polymer dosage per solids concentration. This indicates that it may be beneficial to slightly reduce the extent of thickening of sludge prior to conditioning and dewatering in some cases, e.g. in centrifuge dewatering or in cases when the thickened sludge concentration approaches $m_{a,max}$.

The effect of solids concentration on apparent viscosity, turbidity and optimum polymer dosage could be modelled by eq. 1, when proportionality factors were introduced between m_d and μ_a and polymer dosage, respectively. It is therefore expected that the model may be applied for prediction of optimum polymer doses as a function of both solids concentration and turbulent shear.

The shear sensitivity k_{SS} by definition quantifies the turbidity to solids mass ratio, and should thus be related to conditioner requirement for given $m_{a,max}$, solids concentration and shear. The parameter is suggested as a suitable moniyoring parameter, indicative of the interaction energy between sludge particles, and would be valuable also for testing alternative means of turbidity reduction as e.g. pre-conditioning with inorganic salts.

Acknowledgements

The work has been conducted as part of a Ph.D. study funded by Aalborg University. The authors are grateful for the technical assistance in the laboratory provided by M. Buus and for helpful co-operation with Gunnar Tholstrup, Århus Municipality Environmental Department, Waste Water Lab.

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