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BY:
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NATIONAL WATER RESEARCH INSTITUTE
INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

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B. Q. Liao[1*], I. G. Droppo[2], G. G. Leppard[2,3] and S. N. Liss[4]

ABSTRACT

The effect of solids retention time (SRT) (4-20 days) on sludge floc structure, size distribution and morphology in laboratory-scale sequencing batch reactors (SBRs) receiving a glucose-based synthetic wastewater was studied using image analysis in a long-term experiment over one year. The number of random counted sludge flocs, if less than 800, had a significant impact on measured median floc sizes. Floc size distribution (>10 μm) could be characterized by a log-normal model for no bulking situations, but a bi-distribution of floc size was observed for modest non-filamentous bulking situations. In each operating cycle of the SBRs, the variation in food (F)/microorganisms (M) ratio (0.03-1.0) had no significant influence on floc size distribution and morphology. The results from a long-term study over one year showed that no clear relationship existed between SRT and median floc size based on frequency. However, sludge flocs at the lower SRTs (4-9 days) were much more irregular and more variable in size with time than those at higher SRTs (16 and 20 days). A smaller median floc size was related to a relatively higher level of production of extracellular polymeric substances. A higher sludge volume index was associated with a smaller median floc size.

NWRI RESEARCH SUMMARY

Plain language title

How floc size and morphology changes with age during wastewater treatment processes: impact on treatment performance.

What is the problem and what do scientists already know about it?

Sludge retention times are often varied based on nutrient and sediment characteristics to optimize settling. While the effects of this is measured based on the sludge volume index (settled volume over a given time), the impacts of such temporal changes is not well defined for floc structure. As changes in floc structure influence floc settling behaviour it is important to gain more information on how sludge retention times influence floc structure.

Why did NWRI do this study?

The study was undertaken to improve our understanding of wastewater treatment systems so that optimal operating procedures can be determined.

What were the results?

The results from the one year study showed that no clear relationship existed between sludge retention time (SRT) and median floc size based on frequency. However, sludge flocs at the lower SRTs (4-9 days) were much more irregular and more variable in size with time than those at higher SRTs (16 and 20 days). A smaller median floc size was related to a relatively higher level of production of extracellular polymeric substances. A higher sludge volume index was associated with a smaller median floc size.

How will these results be used?

The published results will be used to optimize wastewater treatment systems.

Who were our main partners in the study?

Lakehead University and Ryerson University.

Effet du temps de rétention des matières solides sur la structure et les caractéristiques des flocs de boues dans les réacteurs discontinus

B. Q. Liao[1*], I. G. Droppo[2], G. G. Leppard [2,3] et S. N. Liss [4]

RÉSUMÉ

L'effet du temps de rétention des matières solides (TRMS) (4-20 jours) sur la structure, la granulométrie et la morphologie des flocs de boues dans des réacteurs discontinus (RD) de laboratoire alimentés en eaux usées synthétiques à base de glucose a été étudié par une analyse d'images dans une expérience à long terme d'une durée d'un an. Le nombre de flocs de boues comptés aléatoirement, quand il était inférieur à 800, avait un effet important sur leur taille médiane mesurée. La granulométrie des flocs (> 10 µm) pouvait être caractérisée par un modèle log-normal en l'absence de foisonnement, mais une double distribution de tailles de floc a été observée en présence d'un faible foisonnement non filamenteux. Dans chaque cycle de fonctionnement des RD, la variation du rapport aliments/microorganismes (rapport F/M) (0,03-1,0) n'a eu aucun effet important sur la granulométrie et la morphologie des flocs. Les résultats d'une étude à long terme d'une durée d'un an n'ont révélé aucun lien évident entre le TRMT et la taille médiane des flocs sur la base de la fréquence. Toutefois, les flocs de boues étaient beaucoup plus irréguliers et de tailles plus variables avec le temps aux TRMT brefs (4-9 jours) qu'aux TRMT longs (16 et 20 jours). Une petite taille médiane des flocs était associée à un niveau relativement plus élevé de production de substances polymériques extracellulaires. Un indice volumique élevé pour les boues était associé à une petite taille médiane des flocs.

Sommaire des recherches de l'INRE

Titre en langage clair

Comment la taille et la morphologie des flocs changent avec le temps durant le traitement des eaux usées : répercussion sur la performance de traitement.

Quel est le problème et que savent les chercheurs à ce sujet?

On fait souvent varier le temps de rétention des matières solides selon les caractéristiques des nutriants et des sédiments afin d'optimiser la sédimentation. Bien que l'effet produit soit mesuré en se basant sur l'indice volumique des boues (volume décanté durant une période donnée), les effets de ces changements temporels n'est pas bien défini pour la structure des flocs. Étant donné que les changements de structure des flocs influent sur leur comportement de sédimentation, il est important de mieux connaître l'effet du temps de rétention des matières solides sur leur structure.

Pourquoi l'INRE a-t-il effectué cette étude?

L'étude a été entreprise en vue d'améliorer nos connaissances des systèmes de traitement des eaux usées afin d'établir des procédures d'exploitation optimales.

Quels sont les résultats?

Cette étude d'une durée d'un an n'a montré aucun lien évident entre le temps de rétention des matières solides (TRMS) et la taille médiane des flocs sur la base de la fréquence. Toutefois, les flocs de boues étaient beaucoup plus irréguliers et de tailles plus variables avec le temps aux TRMT brefs (4-9 jours) qu'aux TRMT longs (16 et 20 jours). Une petite taille médiane des flocs était associée à un niveau relativement plus élevé de production de substances polymériques extracellulaires. Un indice volumique élevé pour les boues était associé à une petite taille médiane des flocs.

Comment ces résultats seront-ils utilisés?

Les résultats publiés seront utilisés pour améliorer les systèmes de traitement des eaux usées.

Quels étaient nos principaux partenaires dans cette étude?

Université Lakehead et université Ryerson.

Effect of Solids Retention Time on Structure and Characteristics of Sludge Flocs in Sequencing Batch Reactors

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ABSTRACT

The effect of solids retention time (SRT) (4-20 days) on sludge floc structure, size distribution and morphology in laboratory-scale sequencing batch reactors (SBRs) receiving a glucose-based synthetic wastewater was studied using image analysis in a long-term experiment over one year. The number of random counted sludge flocs, if less than 800, had a significant impact on measured median floc sizes. Floc size distribution (>10 μm) could be characterized by a log-normal model for no bulking situations, but a bi-distribution of floc size was observed for modest non-filamentous bulking situations. In each operating cycle of the SBRs, the variation in food (F)/microorganisms (M) ratio (0.03-1.0) had no significant influence on floc size distribution and morphology. The results from a long-term study over one year showed that no clear relationship existed between SRT and median floc size based on frequency. However, sludge flocs at the lower SRTs (4-9 days) were much more irregular and more variable in size with time than those at higher SRTs (16 and 20 days). A smaller median floc size was related to a relatively higher level of production of extracellular polymeric substances. A higher sludge volume index was associated with a smaller median floc size.

Keywords: Activated sludge, floc size distribution, morphology, nanoscale, solids retention time, sequencing batch reactors

INTRODUCTION

Activated sludge flocs are particulate aggregates consisting of microorganisms, extracellular polymeric substances (EPS), organic and inorganic colloidal particles (Unz, 1987; Urbain *et al.*, 1993; Liss *et al.*, 1996). They are formed through a dynamic process involving EPS and collisions. In the activated sludge process, it is the behavior of sludge flocs that determines the efficiency of biosolids/liquid separation.

Floc structure, like size and morphology, plays an important role in determining the efficiency and economics of the activated sludge process. Large and dense flocs are always desirable for good settling and dewatering. A higher turbidity in treated effluent is associated with the presence of a larger portion of single or fine clumps of flocs. The poorer dewaterability of sludge is related to a larger amount of fine flocs in sludge (Karr and Keinath, 1978; Lawer *et al.*, 1986; Knocke and Zentkovich, 1986; Olboter and Vogelphol, 1993). Small flocs not only clog the pore structure in the sludge cake but also increase the amount of bound water (Liao *et al.*, 2000) The morphology of activated sludge has been related to the traditional settling index (Eriksson and Hardin, 1984; Watanabe *et al.*, 1990; Grijspeerdt and Verstraete, 1997). A smaller form factor (more irregular flocs) is correlated to a larger sludge volume index (SVI) (Grijspeerdt and Verstraete, 1997).

It is not surprising that considerable efforts have been made to improve the understanding of floc structure, considering its importance in biosolids/liquid separation. However, most of the previous studies focused on an understanding of the size range and morphology with sludge samples directly from full-scale activated sludge plants and with little experimental control. The variability in floc size and morphology with respect to the environmental and operating conditions has not been well understood. In recent years, a few studies were conducted under controlled conditions. The configurations used in these studies are continuous stirred tank reactors (CSTR) operated at a steadystate condition (Andreadakis, 1993; Barbusinski and Koscielniak, 1995; Wilsen and Balmer, 1999). For most situations, the effect of filamentous microorganisms, which affect the settling and dewatering properties of sludge flocs (Sezgin *et al.*, 1978) [15], was not minimized or eliminated.

The formation-deformation of activated sludge flocs is a highly dynamic process, depending on the microbial community structure, environmental and operating conditions. Consequently, it is desirable to know how floc structure response to changes in environmental and operating conditions. The sequencing batch reactor (SBR) is operated in a controlled cyclic manner, a different operating model as compared to the conventional CSTR and plug flow reactor (PFR). As a result, the SBR is an ideal tool to study the influence of shocking organic loading on floc structure in a controlled periodic operation. On the other hand, the SBR is increasingly recognized as a persuasive option in municipal and industrial wastewater treatment. The optimal operation of SBR systems suffers from detailed fundamental information of how the cyclic operation affecting floc structure, which influences the settling and dewatering properties.

The purpose of this study was to investigate the effect of cyclic operation on floc size distribution and morphology at different SRTs, and to study the potential correlation among median floc size and other sludge properties, such as EPS production and sludge volume index (SVI), using well-controlled laboratory-scale SBRs.

MATERIALS AND METHODS

Sequencing Batch Reactors

The laboratory experimental system consists of four parallel SBRs (effective volume 2L each) with both on-line pH and temperature controllers. A synthetic wastewater containing glucose and inorganic nutrients was used as feed. The SBRs were operated at a hydraulic retention time of 4 hours but at different SRTs (4 to 20 days) for more than a one-year period. Dissolved oxygen (DO) concentration in each SBR was maintained at a level of > 2.5ppm. The mixing intensity in each SBR was similar by setting the same rotating speed of magnetic stirring bar on the bottom of each SBR and monitoring the amount of air to each SBR.

Performance and stable operating conditions of the SBRs were determined by monitored the mixed liquor suspended solids (MLSS), volatile suspended solids (VSS), effluent chemical oxygen demand (COD), effluent suspended solids (ESS), and sludge volume index (SVI). Typically, a period of three to four SRTs was required to reach stable operating condition in each SBR. Detailed information of the SBR system and operating conditions can be found in Liao *et al.* (2001).

Filamentous Microorganisms

The abundance of filamentous microorganisms was extensively examined with a light microscope (Olympus, BH2-RFCA) at a magnification of X 400. The number of filaments was classified into levels 1 to 6 according to Jenkins *et al.* (1993). A smaller score corresponds to a lower level of filaments. Microscopic observations showed that sludge samples contained low levels of filaments (level 0-1).

Floc Size Distribution

The measurement of floc size distribution was based on a modified method originally developed for suspended sediments but applied to sludge flocs (Droppo and Ongley, 1992; Droppo *et al.*, 1996). One drop (0.1 mL) of the sludge sample was taken by using an Eppendorf pipette with an open month pipette tip (3 mm), and mixed with 0.8 mL low melting point agarose (0.75 % w/w) solution in a microcentrifuge tube (1.7 mL). The mixture was poured onto the slide of a plankton chamber immediately. The agarose solidified in less than a minute. The stabilized samples were placed on a

Zeiss Axiovert 100 microscope which was interfaced with a CCD color video camera and the Northern Exposure™ (Empix Imaging Inc.) image analysis system. Measurements were restricted to floc sizes equal or greater than 10 μm. The median floc size was calculated from a minimum of 1000 flocs in each sample.

Morphology

Morphology of sludge flocs was observed and recorded under microscopy at the same time for floc size measurement and characterized by a shape factor (0-1). The shape factor is a parameter describing the deviation of an object from a circle. The value of shape factor is strongly affected by the roughness of boundaries. A circle has a shape factor of 1.

Floc Ultrastructure

Nanoscale observations of floc EPS were made on ultrathin sections of whole flocs (to compare SRTs of 4 and 20 days), which were prepared for transmission electron microscopy (TEM) by the multi-method technique of Liss *et al.* (1996). Measurements were made from preparations derived from flocs fixed initially in 'glutaraldehyde plus ruthenium red (Liss *et al.*, 1996). After the double fixation (designed to minimize extraction and shrinkage), the flocs were embedded in Spurr's epoxy resin, and then sectioned with an RMC Ultramicrotome MT-7 (Boeckeler Instruments, Tucson, AZ). The 70 nm sections were mounted on formvar-covered copper TEM grids, and then counterstained (Liss *et al.*, 1996). The searches of TEM views of flocs, to select representative images of ultrastructural features, were done systematically according to the protocol of Leppard *et al.* (2003). Documentation was performed with a JEOL 1200 EXII TEMSCAN scanning transmission electron microscope (JEOL, Peabody, MA) operated in transmission mode at 80 kV.

Extracellular Polymeric Substances

EPS from sludge flocs were extracted by a cation ion exchange resin (Dowex-Na form) method (Frølund *et al.*, 1996; Bura *et al.*, 1998). Total carbohydrates, proteins, acidic polysaccharides and DNA were measured in the extracted EPS (Liao *et al.*, 2001). The sum of total carbohydrates, proteins and DNA contents in the EPS was calculated as an estimate of the total EPS content. Carbohydrate, protein and DNA are considered to be the dominant components of the EPS (Forster, 1983; Urbain *et al.*, 1993; Frølund *et al.*, 1996; Liao *et al.*, 2001).

Sludge Volume Index

The compressibility of sludge from the bench-scale SBRs was evaluated by the SVI. The SVI measurements were performed in 250 mL graduated cylinders with mixed liquor samples directly from the SBRs at the end of the reaction phase. The biomass concentration for the SVI determination was in the range of 2000 ± 300 mg/L, in which range the effect of biomass concentration on the SVI is not important (Lovett *et al.*, 1983).

Standard Wastewater Analysis

Mixed liquor suspended solids (MLSS), volatile suspended solids (VSS), effluent suspended solids (ESS) and chemical oxygen demand (COD) were determined in accordance with Standard Methods (APHA, 1992).

Statistic Analysis

An analysis of variance (ANOVA) was used to test the difference in median floc size in terms of SRT. Correlations among different sludge properties (median floc size, EPS and SVI) were determined using a distribution-free statistic (Spearman's coefficient of rank correlation, r_s) (Barber and Veenstra, 1986). The significance of correlation was established at a 95% confidence level.

RESULTS AND DISCUSSION

Previous studies indicate that the activated sludge floc size covers a broad range from 0.5 to more than 1000μm (Li and Ganczarczyk, 1990 and 1993). It is therefore difficult to give a full characterization of floc sizes by a single technique. Different techniques have to be used for the accurate determination of floc size in different size ranges. For small flocs (<10μm), a coulter counter technique is necessary for accurate measurement and usually the errors associated with small floc size determination are large (Li and Ganczarczyk, 1990 and 1993). In this study, the measurement was restricted to floc size equal to or larger than 10μm, due to the limitation of the microscopy magnification (25×) used in this study and the fact that flocs larger than 10μm are the main source of surface area, volume and mass in activated sludge (Li and Ganczarczyk, 1993; Barbusinski and Koscielniak, 1995).

Effect of the Counted Floc Number on Floc Size Distribution

For floc size distribution measurement, it is important to make sure that the results are statistically relevant, i.e. enough flocs have to be counted. Therefore, it is necessary to known the effect of the counted floc number on floc size distribution. The results are shown in Figure 1. The relative errors of median floc sizes were significantly affected by the counted floc number. The relative errors reached a constant value (±2%) only when the number of the counted flocs was large enough (>800 flocs). The minimum number of flocs, which shows no significant effect on floc size distribution, is much larger than what some previous studies measured. In this study, the counted number of flocs in each sample was more than 1000. Greater than 70,000 flocs were counted which covered a long-term experimental time over one year.

Mathematical Description of Floc Size Distribution

At present, a number of different mathematical models have been proposed to describe the size distribution of sludge flocs, i.e. Rosin-Rammler, Half-normal, power-law and exponential models (Li and Ganczarczyk, 1990 and 1993; Barbusinski and Koscielniak, 1995; Wilen and Balmer, 1999). The Wilk-Shapiro test was applied to test the validity of log-normal distribution for floc size measurements in this study. It was found that the floc size distribution followed the log-normal function for sludge samples at SRTs 9, 12, 16, 20 days (Figure 2), while the size distribution of sludge samples from SRTs 4, 6 days did not fit the log-normal model all the time and showed a more broad and irregular distribution at non-filamentous bulking situations (Figure 3). A bi-distribution model, as observed in the study of Jorand *et al.* (1995), was found to be more appropriate for description of floc size distribution for modest non-filamentous bulking sludge at lower SRTs (4 and 6 days). This result is consistent with the findings of Li and Ganczarczky (1990) and Barbusinski and Koscieliniak (1995) and Wilen and Balmer (1999) in that the log-normal distribution function is the best model for flocs larger than 10μm. However, the log-normal distribution function did not fit floc size distribution of sludge at modest non-filamentous bulking situation.

Variation in Floc Size in Each Operating Cycle

Unlike the continuous stirred tank reactors (CSTR) used in previous studies (Andreadakis, 1993; Barbusinski and Koscielniak, 1995; Wilsen and Balmer, 1999), the cyclic operation of SBRs determines a dynamic nature of the SBR process. The ratio of F (food)/M (biomass) changes dramatically with time in each cycle. The median floc sizes of sludge at different reaction times are shown in Figure 4. No significant difference was observed in terms of reaction time, which corresponds to an F/M ratio of 0.04 -0.5 (SRT=9days) and 0.03-0.25 (SRT=20days) kg COD/kg MLSS/d in each cycle. This result suggests that floc size distribution was not sensitive to the variation in F/M in one cycle or to the short-term shock of COD in the SBRs. In contrast, Barbusinski and Koscielniak (1995) found the mean floc size changed dramatically under varying F/M conditions in a CSTR. A direct comparison between these two studies might be difficult, due to changes in conditions, especially in the type of configuration (SBR vs. CSTR) used. Barbusinski and Koscielniak (1995) found the long-term loading changes caused larger disturbances to the floc size distribution than more rapid but shorter ones. The results from this study may suggest that floc sizes from SBR systems were more stable to the short-term shock of organic concentration in wastewaters, as compared to the flocs in the CSTR systems, because microorganisms in SBR grow in a typical dynamic process and are used to the dramatic change in F/M conditions. From the practical viewpoint, the stability of floc sizes to the dynamic organic loading conditions is important for effective separation of flocs from treated effluent. The SBR may be more stable than the CSTR in biological wastewater treatment processes from the floc size point of view.

Effect of Solids Retention Time on Floc Size Distribution

The long-term effect of SRT on floc size distribution is reflected by the variation in mean floc sizes at different SRTs, as shown in Figure 5. Changes in floc size distribution were observed, particularly for sludge at lower SRTs (4 and 6 days), with respect to elapsed time. There was no clear relationship between SRT and median floc size based on frequency (Figure 5). But a general tendency observed is that floc size distribution was more stable with respect to experimental time at higher SRTs (9-20days), as reflected by the smaller standard deviation (Figure 5). The floc size distribution at SRTs large than 9 days has a much more uniform shape of the log-normal distribution, as compared to that at the lower SRTs (4, 6 days).

The stability of floc size distribution at different SRTs might be explained by the growth rate of cells. At lower sludge age, more substrates are available for sludge microorganism growth. Therefore, more microcolonies are formed on the surface of floc until the mass of floc is big enough to be broken into smaller flocs. While at higher SRTs, the substrate is limited for the growth of sludge and starved conditions produce a more stable biomass.

Effect of Solids Retention Time on Floc Morphology

Extensive examinations of activated sludge flocs from different SBRs under microscopes showed that flocs at lower SRTs (4,6 days) were much more irregular with a cylinder shape, while a spherical and more compacted floc structure was observed for flocs at higher solids retention time (9, 12, 16, 20 days). A quantitative description of floc morphology at different SRTs is reflected by the shape factor distribution as shown in Figure 6. It is clear that at the lower SRTs a significant part of flocs has a shape factor less than 0.2 as compared to the flocs at the higher SRTs. This result is consistent with the observation of Eriksson and Hardin (1984).

Although the floc characteristic size had no statistically significant difference in term of SRT, changes in floc size with experimental time were observed, especially with the lower SRTs (4 and 6 days) or the higher organic loading intensity conditions. A change in the production of EPS was observed when there was a significant change in floc size distribution. Figure 7 shows the correlation between the median floc size and the EPS content. A smaller median floc size is related to a larger amount of EPS produced. This result indicated that the production of a larger amount of EPS could prevent the formation of larger flocs, which is consistent with the observation of Harris and Mitchell (1973 and 1975) in that polymers produced by bacteria could stabilize the sludge suspension from flocculation.

Floc Ultrastructure Under Different SRTs

Both populations of flocs examined by TEM (4 days vs 20 days SRT) showed some diversity in morphology, but a pronounced difference between populations in surface roughness is revealed by nano-scale resolution. Despite variations within a population, a difference in floc roughness becomes evident when one compares ca. 100 flocs from each of the two populations representing extremes of SRT. Figure 8 reveals patches of a nanoscale surface layer which is present commonly on flocs of 20 days SRT, but rarely on flocs of 4 days. The floc interface with the bulk water phase is highly porous in Figure 8a, with EPS fibrils being sufficiently sparse to permit considerable contact between the bulk water milieu and bacteria at the floc periphery. By comparison, floc surface roughness is minimized in Figure 8b where EPS colloids coalesce in patches to form a nanoscale surface layer. The roles of EPS in surface roughness and other surface properties, with regard to the chemistry and physical packing of principal EPS colloids, are worthy of an extended investigation.

The Relationship Between Floc Structure and Sludge Volume Index

It has found that the settling properties of sludge flocs are strongly affected by floc structure (size, density, shape) (Eriksson and Hardin, 1984; Watanabe *et al.*, 1990; Andreadakis, 1993; Grijspeerdt and Verstraete, 1997). An examination of floc characteristic size and sludge volume index (SVI) data shows that a strong correlation exists between these two parameters (Figure 9). A higher SVI was associated with a smaller median floc size (d50, frequency). This is, however, inconsistent with the results as reported in the literature (Andreadakis, 1993). A comparison might be difficult, as the filaments level was different in these two studies. The result, as shown in Figure 9, could be explained by considering the flocculating ability of sludge microorganisms in which larger and denser flocs is related to a better settling and compressibility.

CONCLUSIONS

The influence of SRT or F/M on sludge floc structure, size and morphology was studied in well-controlled laboratory-scale SBRs over one year. The results can be summarized as followings:

1.) The number of counted flocs has a significant effect on the floc characteristic parameters such as the median sizes based on frequency, volume and surface area. Under tested conditions, a minimum number of 1000 flocs in image analysis were counted for each sample, in order to eliminate the effect of the counted floc number on floc size distribution.

2.) For most situations, floc size distribution could be described by the log-normal model. However, a bi-distribution model gave better description of sludge floc size distribution for modest non-filamentous bulking situations.

3.) In each operating cycle, there was no significant change in floc size distribution and morphology in terms of the reaction time.

4.) Under tested conditions, there was no clear relationship between SRT and median floc size in the SBRs. This was also supported by the stable floc size distribution in each cycle and at different SRTs. All these results suggest that the SBRs were not sensitive to the shocking operation of organic loading from a floc size point of view.

5.) The morphology of sludge flocs at the lower SRTs was usually more irregular than that at the higher SRTs. This is reflected by the presence of a larger portion of flocs having a shape factor less than 0.2 at the lower SRTs

6.) Nano-scale structural observations might improve the interpretation of results based on chemical data and micro-scale structure.

7.) A smaller median floc size was associated with a higher SVI.

8.) The median floc size was affected by the EPS content. A smaller median floc size (frequency) was associated with a larger amount of EPS. This result indicates that the presence of a large amount of EPS could stabilize the sludge suspension (dispersion).

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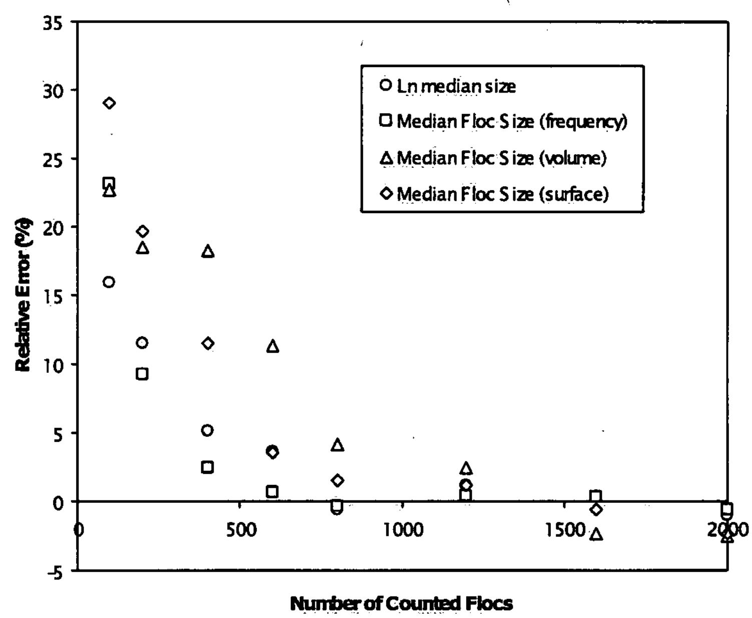
A List of Figures



Ln median size
Median Floc Size (frequency)
Median Floc Size (volume)
Median Floc Size (surface)
Relative Error (%)
Number of Counted Flocs
35
30
25
20
15
10
5
0
-5
0
500
1000
1500
2000

Figure 1

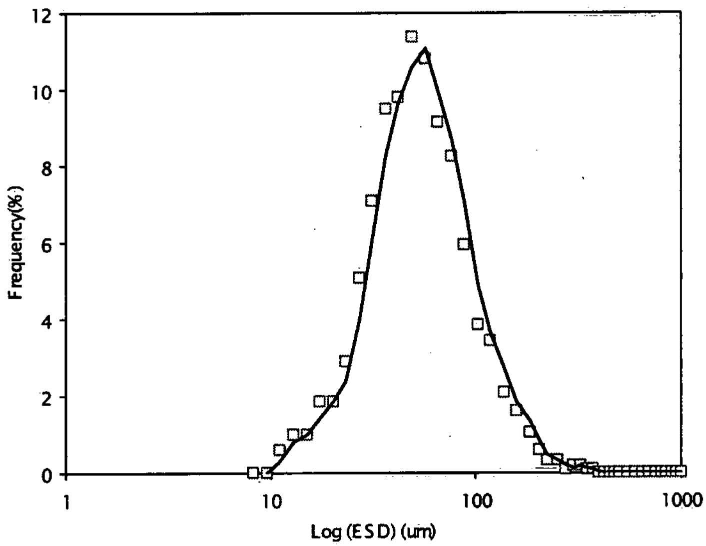


Figure 2

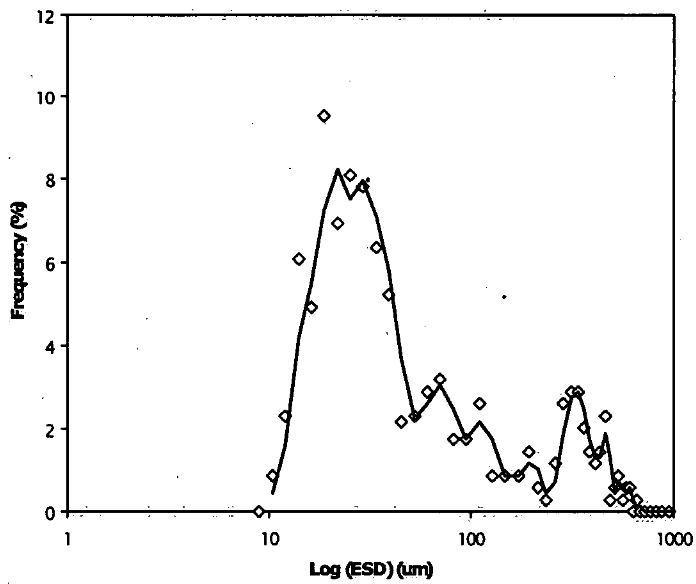


Figure 3

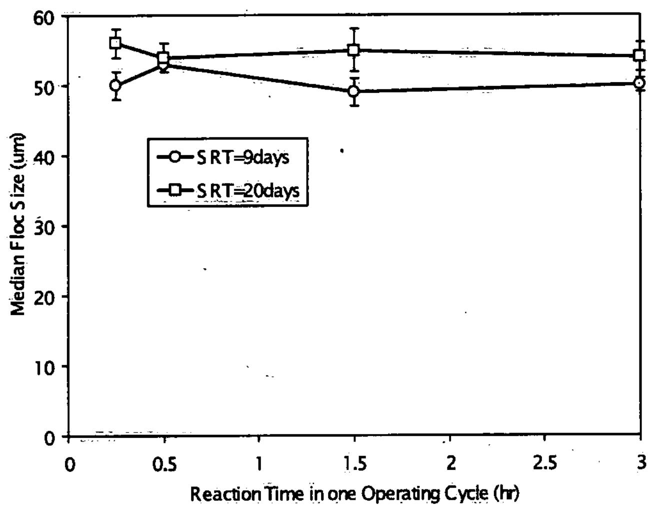

60
50
40
30
20
10
0
Median Floc Size (um)
SRT=9days
SRT=20days
0
0.5
1
1.5
2
2.5
3
Reaction Time in one Operating Cycle (hr)

Figure 4

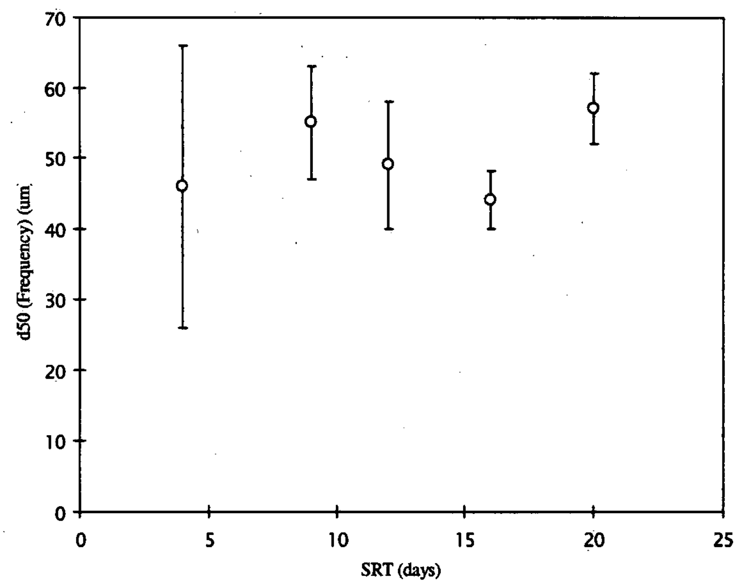
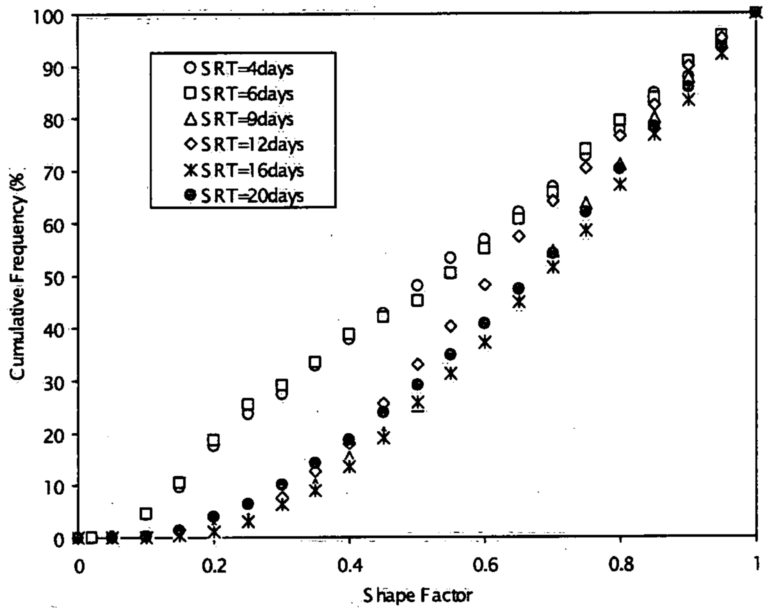
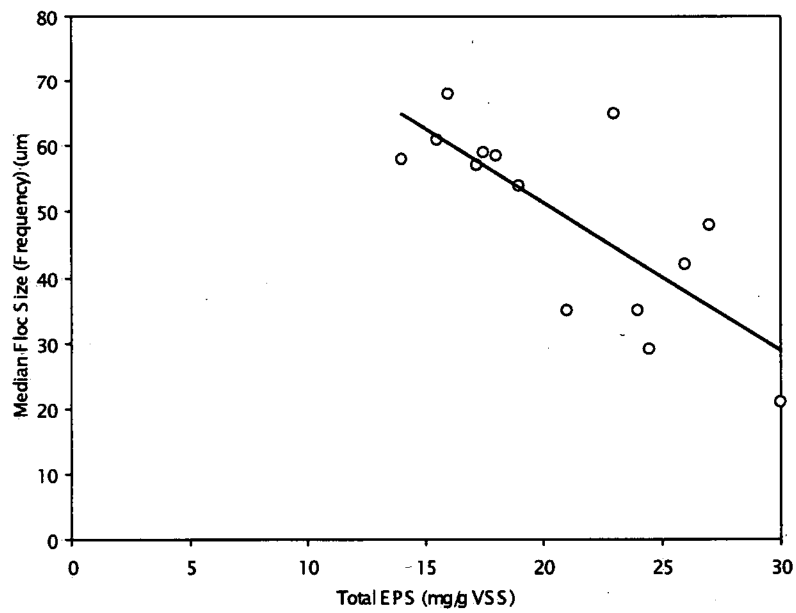


Figure 5



100
90
80
70
60
50
40
30
20
10
0
Cumulative Frequency (%
SRT=4days
SRT=6days
SRT=9days
SRT=12days
SRT=16days
SRT=20days
0
0.2
0.4
0.6
0.8
1
Shape Factor

Figure 6



80
70
60
50
40
30
20
10
0
Median Floc Size (Frequency) (um
0
5
10
15
20
25
30
Total EPS (mg/g VSS)

Figure 7

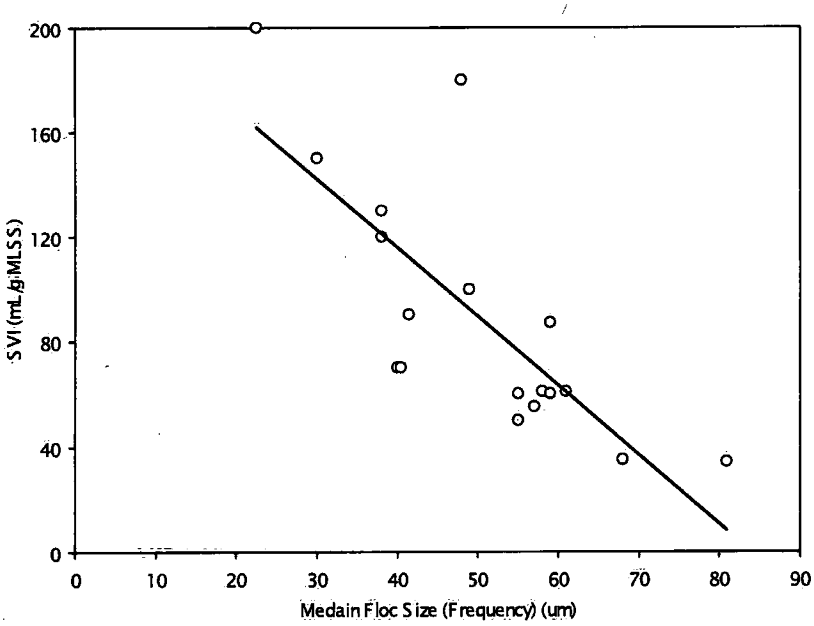
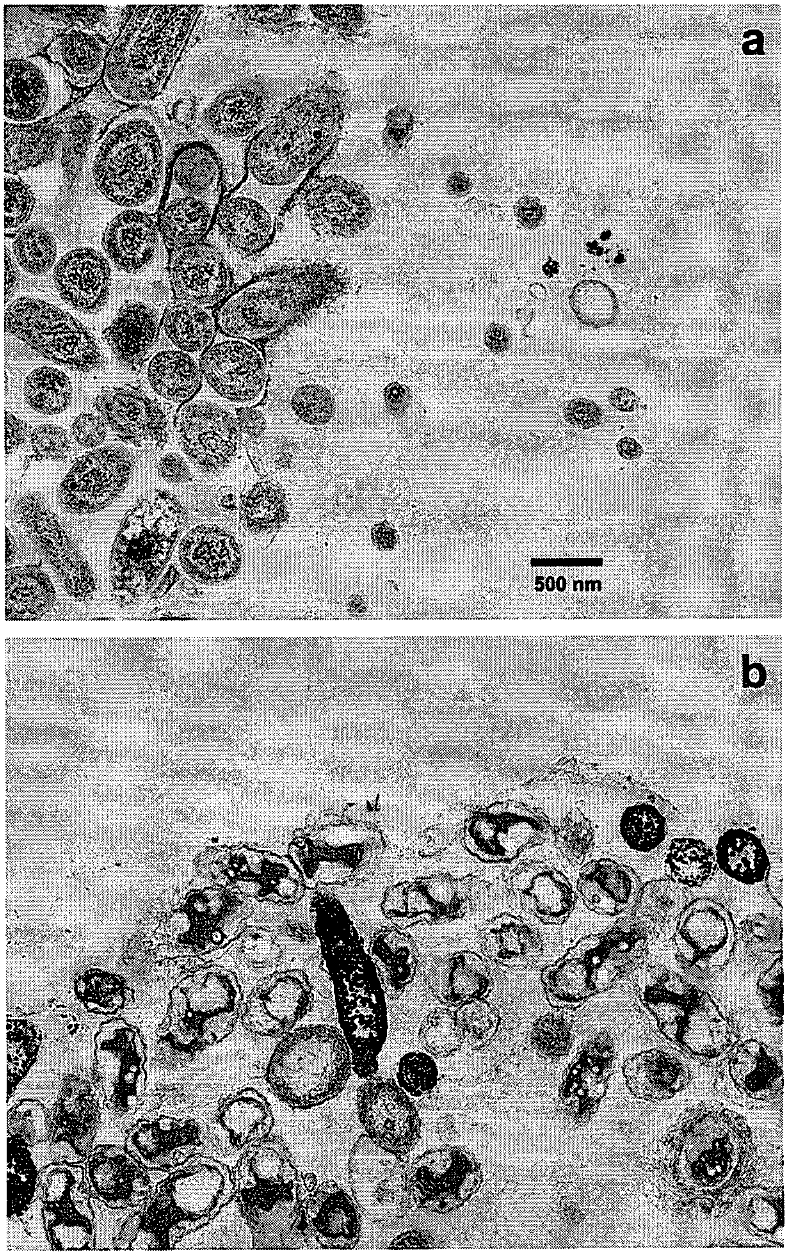

200
160
120
80
40
0
SVI (mL/g MLSS)
0
10
20
30
40
50
60
70
80
90
Medain Floc Size (Frequency) (um)

Figure 9


a
500 nm
b

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