The Relationship Between Mixed-Liquor Particle Size and Solids Retention Time in the Activated Sludge Process

Licheng Chan[1], Shao-Yuan Leu[1*], Diego Rosso[2], Michael K. Stenstrom[1]

ABSTRACT: Particle size distribution (PSD) analysis was used to evaluate the quality of mixed liquors collected from different activated sludge process modifications (i.e., conventional activated sludge, modified Ludzack-Ettinger, high-purity oxygen, step-anoxic, and oxidation ditch). An experiment protocol was developed to define the allowable sample holding time and provide representative and repeatable results. Samples of 26 treatment plants, with a total of 37 samples, were tested. A new indicator, called *mean particle size* (MPS), was introduced to describe the integrated mean particle size. The results of MPSs of three cut-off sizes (0.5 to 50, 100, and 200 μm) showed that the average size of mixed-liquor biosolids increased with increasing solids retention time (SRT), and the number of particles in the sedimentation supernatant decreased with increasing SRT. Particle deflocculation occurred after excessive sample holding time, and analysis within 12 hours generally eliminated sample holding problems. The results provide a methodology using PSD for characterizing mixed-liquor biosolids. *Water Environ. Res.*, **83,** 2178 (2011).

KEYWORDS: particle size distribution, solids retention time, wastewater treatment.

doi:10.2175/106143011X12928814445339

Introduction

Conventional activated sludge processes (ASPs) operating at short solids retention times (SRTs) (1 to 2 days) are common in the United States and are considered the secondary treatment processes of choice in many locations. The ASPs operation at long SRTs is considered only for nitrogen removal, but many studies have shown several additional benefits of long SRT operation, including more reliable operation (with selectors), improved effluent quality with respect to emerging contaminants (Bolong et al., 2009; Petrovic et al., 2003), and improved oxygen-transfer efficiency (Leu et al., 2011; Rosso and Stenstrom, 2005; Rosso et al., 2005). Some of the benefits of long SRT operation (combined with anoxic/anaerobic selectors) for improving biosolids composition and quality have been discussed previously (Jenkins et al., 2004; Palm et al., 1980). This paper extends the earlier work using particle size analysis to quantify benefits.

[1*] Civil and Environmental Engineering Department, University of California, Los Angeles, CA, 90095, U.S.A.; e-mail: syleu@ucla.edu.

[2] Civil and Environmental Engineering Department, University of California, Irvine, California.

Particle size is an important indicator to assessing water quality, and it can be related to several characteristics of pollutants for wastewater treatment, such as settleability, turbidity, growth of microorganisms, and absorption/adsorption capacity of adsorbents. Smaller particles with high organic content can adsorb more pollutants, such as heavy metals, polynuclear aromatic hydrocarbons, emerging contaminants, and/or chlorinated pesticides (e.g., DDT) (Bentzen and Larsen, 2009; Han et al., 2006; Liu et al., 2009; Schorer, 1997). Particle size analysis also has been used to evaluate the performance of filtration and optimize UV disinfection systems (Bourgeous et al., 2003) and is being used extensively in stormwater management (Li et al., 2005).

Particle size distribution (PSD) analysis is a useful tool to characterize the ''healthiness'' of activated sludge. Biosolids particle sizes range from 0.5 μm (single cell) to 1 mm (Metcalf & Eddy, 2003), and a healthier or more desirable sludge should consist of fewer numbers of very small particles. Several previous investigations have discussed the benefits of better biosolids structure on treatment performance and the parameters influencing the biosoilds structure. Bisogni and Lawrence (1971) delineated the relationships of three settling properties of biosolids and SRT (i.e., sludge volume index [SVI], percent dispersion, and zone settling velocity) and defined an optimal SRT from 4 to 9 days. Chao and Keinath (1979) and Knocke and Zentkovich (1986) showed that larger particles were generated from long SRT reactors (8 to 10 days), which can provide better dewatering characteristics.

Dissolved oxygen concentration and organic loadings also influence the settling properties of biosolids. Wilén and Balmér (1999) investigated the effects of increasing dissolved oxygen to larger particles and the benefits of improved settling properties of biosolids. Barbusiński and Kościelniak (1995) showed that the average size of flocs increased with the loading intensity of substrate. Both dissolved oxygen and organic loading are the key factors to the growth of filamentous bacteria (Jenkins et al., 2004; Metcalf & Eddy, 2003).

The PSD analysis is of great interest to treatment plant operation, but the testing methodology has not been well-developed yet. Therefore, the goals of this paper are to verify the following two hypotheses of using PSD analysis for the ASPs:

(1) Larger mean biosolids particle size is associated with longer SRT, and
(2) Fewer effluent particles are associated with larger mean particle size.

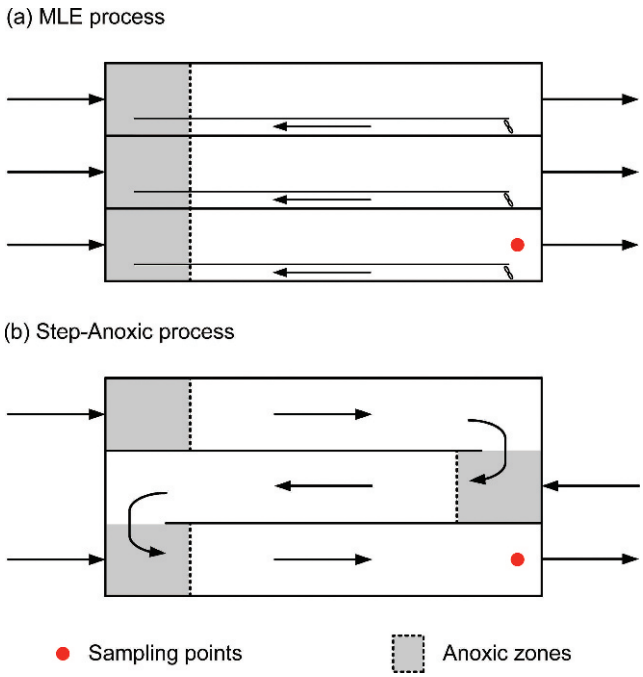

Figure 1—Sampling locations of two wastewater treatment processes: (a) MLE process, and (b) step-anoxic process. The spots show the sampling points, and the shaded areas show the anoxic zones. To simulate the effluent sludge to the secondary clarifiers, samplings for all processes were collected from the aeration tanks close to the ends of the aerobic zones.

To evaluate these hypotheses, mixed-liquor samples collected from 26 wastewater treatment plants (WWTPs) were tested. All of the WWTPs are on the west coast of the United States or Canada and are operating at different SRTs, with several process modifications, such as step-anoxic or modified Ludzack-Ettinger (MLE). A protocol for PSD analysis was developed to ensure repeatable analyses and used to evaluate the mixed liquors and mixed-liquor supernatants. The effects of different process modifications (e.g., step-feed) also are noted.

Materials and Methods

Wastewater Treatment Plants. Table 1 shows the background of the tested WWTPs. A total of 26 WWTPs of different treatment processes were tested, which includes 5 conventional processes, 5 high-purity oxygen (HPO) processes, 10 MLE processes, 4 step-anoxic processes, 1 trickling filter–solids contact (TF-solids contact) process, and 1 oxidation ditch process. The conventional, TF-solids contact, and HPO processes were operating at a low SRT, ranging from 1 to 4 days; the MLE, oxidation ditch, and step-anoxic processes were operating at a long SRT, from 5 to 30 days. The range of rated capacities of the tested WWTPs was between 3×10^4 and 1.7×10^6 m^3/d (8 to 450 mgd). Figure 1 shows the locations of sampling points for the MLE processes and step-anoxic process. The samples were collected from aeration tanks close to ends of the aerobic zones. In some cases, duplicate tests were performed at selected treatment plants at different times, and, in total, 37 tests were performed at 26 WWTPs. The 37 tests do not include duplicates taken at the same time.

Table 1—Background of the tested WWTPs.

	Treatment process	SRT (days)	Capacity (10^3 m^3/d)	Test	Holding (hours)
A	Conventional activated sludge	2	41.6	1	4
B	Conventional activated sludge	2	-	1	4
C	Conventional activated sludge	3.5	124.9	1	3
D	Conventional activated sludge	4	136.5	1	4
E	Conventional activated sludge	1	378.5[a]	1	4
F	High purity oxygen	1.5	1703.3	2	11, 31
G	High purity oxygen	1	738.1	1	6
H	High purity oxygen	1.5	685.1	1	28
I	High purity oxygen	2.5	1514.0	1	20
J	High purity oxygen	2	37.9	1	6
K	Modified Ludzak-Ettinger	8	317.9	2	6, 23
L	Modified Ludzak-Ettinger	8.5	16	2	4,6
M	Modified Ludzak-Ettinger	8	56.8	1	3
N	Modified Ludzak-Ettinger	8	632.1	1	6
O	Modified Ludzak-Ettinger	30	24.6	1	3
P	Modified Ludzak-Ettinger	8	49.2	3	3, 3, 6
Q	Modified Ludzak-Ettinger	12	302.8	2	3, 5
R	Modified Ludzak-Ettinger	30	83.3	1	3
S	Step-anoxic	12	-	2	3, 4
T	Step-anoxic	5	378.5[a]	1	6
U	Step-anoxic	12	378.5 in total[b]	3	3, 4, 5
V	Step-anoxic	12		2	4, 4
W	Step-anoxic	12		2	4, 4
X	Step-anoxic	30	-	1	3
Y	TF-solids contact	2.5	-	1	6
Z	Oxidation ditch	12	30.3	1	3

[a] Plants E and T are the same plant but operating at different process modifications at two time periods.
[b] Plants U, V, and W share the same discharge permit, and the total rated capacity is 378 500 m^3/d.

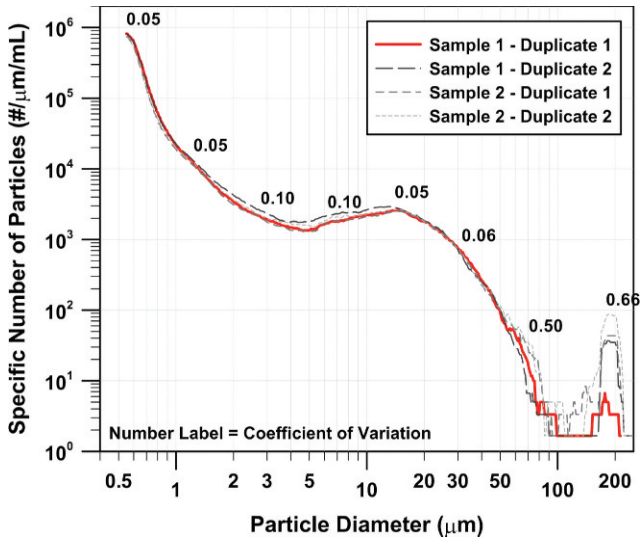

Figure 2—PSDs of mixed-liquor samples from a WWTP (plant D). Two duplicates were performed for two samples. Note that the specific particle number is calculated as the number of particles within certain particle size ranges per milliliter of samples; labels show the coefficient of variation of four measurements. See text for more detail.

Particle Size Distribution Instrument. The PSD analysis was performed using an AccuSizer 780 optical particle sizer module equipped with an autodilution system and a light scattering/extinction sensor (model LE400-0.5SE; Nicomp Particle Sizing Systems, Santa Barbara, California). The instrument can detect particle size as small as 0.5 to 500 μm in diameter. For each experiment, 0.5 mL of mixed-liquor sample was collected using a wide-bore pipette and injected to the dilution chamber of the PSD device. Each sample can be analyzed in 90 seconds if dilution is not required, and longer analysis time may be necessary if the sample concentration exceeds 12 000 #/mL. The instrument automatic dilutes the sample to less than 12 000 #/mL to perform optimal particle counting. Between each PSD test, three auto-flush cycles are used to ensure the cleanness of the dilution chamber and the sensor, which takes approximately 6 minutes to complete. The total time to process one sample is approximately 10 minutes.

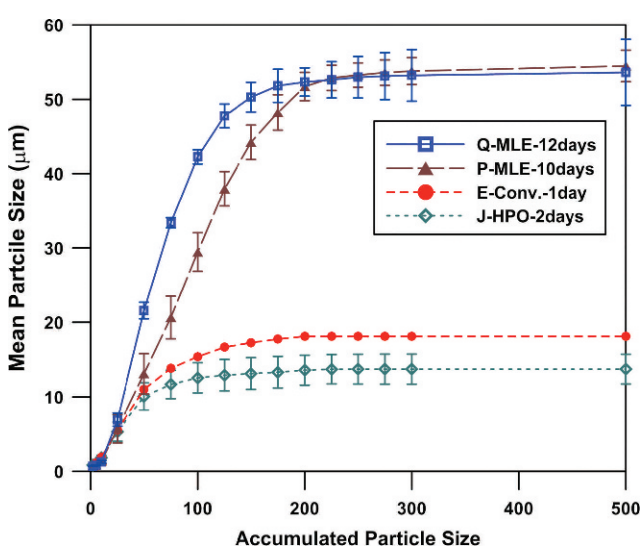

Figure 3—MPSs calculated at different cut-off particle diameters for four WWTPs.

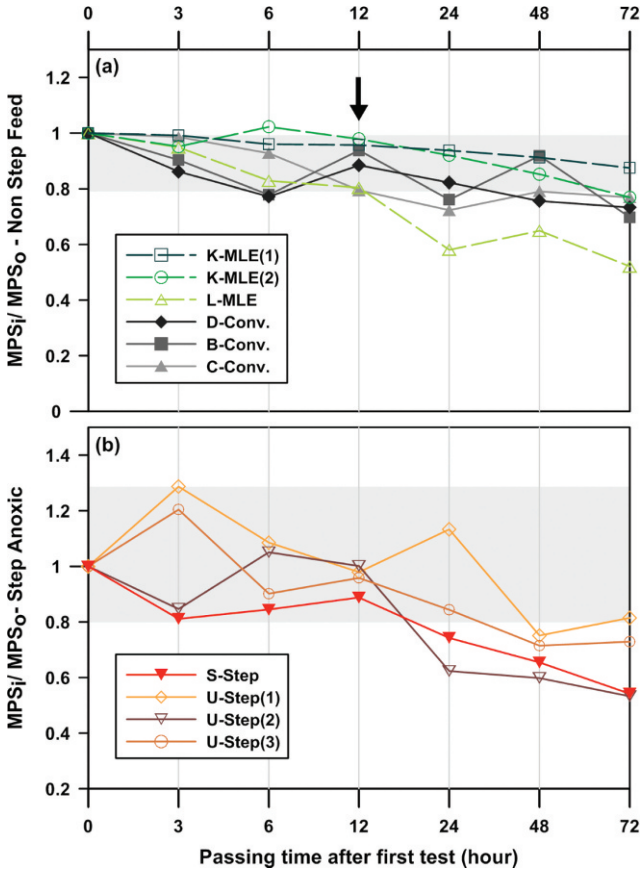

Figure 4—Effects of sample holding time on particle sizes. The MPSs were calculated from 0.5 to 200 μm. MPS_0 is the initial measured MPS, and MPS_i is the MPS over time: (a) MPS of samples from non-step-feed processes show less than 20% reduction in average particle sizes within 12 hours of holding time (as a result of flocculation), and (b) MPS of step-feed processes show less consistency in changing MPS.

Protocol Development. Mixed-liquor samples were collected from the aeration tanks of the WWTPs, close to the end of the secondary processes, using wide-mouth 500-mL sampling bottles. The bottles were filled to approximately 9/10 full to maintain air space to prevent anaerobic conditions. Two duplicate samples were collected at each location to reduce variability when the consistency of measurements was not verified at the initial phases of the investigation.

None of the samples from the tested WWTPs were collected during filamentous bulking events or during process upsets. At these plants, SVI and filament counts are measured routinely, which is the basis for this knowledge. The samples were analyzed at the time of arrival in the laboratory (generally less than 4 hours after collection). To accelerate PSD analysis, the mixed-liquor samples were diluted by 1:10 or 1:50 before analysis. In addition to mixed-liquor particle size analysis, two additional sets of

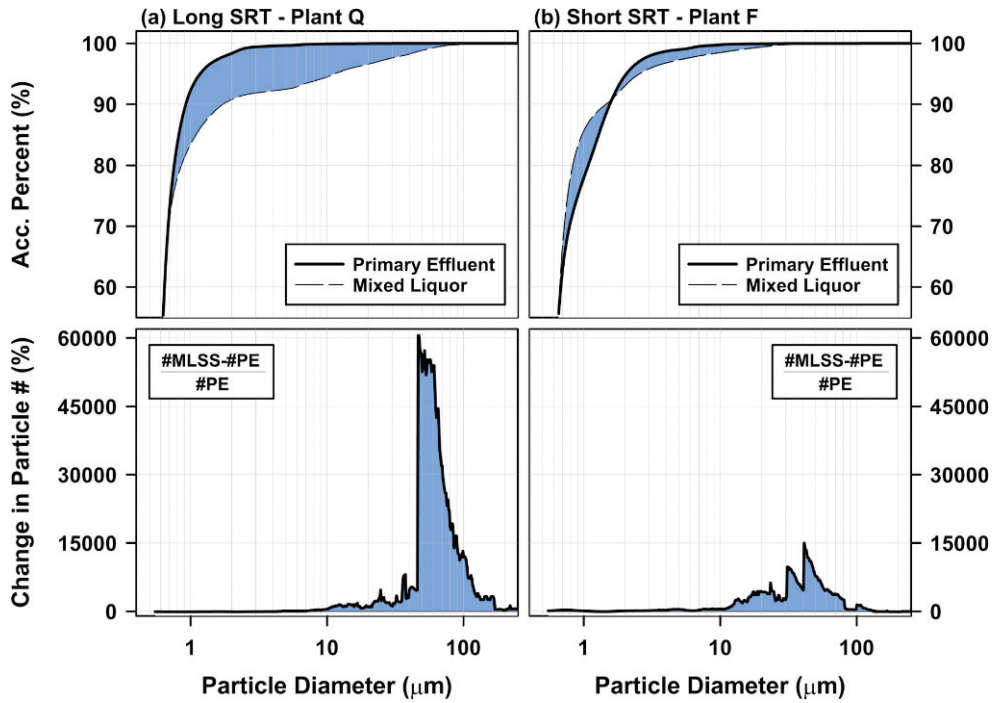

Figure 5—Changes in PSDs before and after secondary treatment.

experiments were performed. The first set was to determine the effect of sample holding time on PSD, to define the experimental protocol, and the second was to determine conditions and the length of settling time needed to obtain results representative of well-operated secondary clarifiers. The two additional tests are discussed first.

(1) Holding time and PSD—72-hour tests. Li et al. (2005) noted that particles in fresh stormwater samples can increase in size after 6 hours of holding. To determine the effect of sample holding time on biosolids particles, 10 samples at the beginning of the study were tested over a period of holding time. After the initial PSD analysis performed immediately after the samples arrival, the samples were allowed to sit on a laboratory bench at room temperature (approximately 20°C) and retested after 3, 6, 12, 24, 48, and 72 hours. Before PSD analysis, the samples were mixed by gentle shaking and inverting in the sample bottle, as recommended in Li et al. (2005). A standard 10-mL pipette having an enlarged (1.42-mm) internal tip diameter was inserted to mid-depth of the sample bottle (approximately 7 to 8 cm under the surface) to collect the samples and tested in the PSD analyzer.

(2) Clarification tests. The procedure for the analyses to estimate clarification was similar to the 72-hour tests, but, instead of testing the mixed liquor, the supernatants (the clarified upper layer of the samples) were tested. After the first PSD test was completed, samples were allowed to settle for 0.5, 1, and 2 hours. At each settling time, supernatant samples were collected with care to avoid disturbing the settled biosolids at a depth of approximately 5 cm from the liquid surface, which typically was near the middle of the clear zone. The same type of 10-mL pipette was used.

Mean Particle Size. This parameter was introduced specifically in this study to evaluate the mixed-liquor samples and was calculated by using the first moment (eq 2) divided by the total particles of the desired range of particle sizes. This methodology is similar to the approach used to calculate the retention time of tracers (Levenspiel, 1967), and the equations are shown as follows:

$$\text{Total Particles} = \int_{0.5}^{M} Nds \tag{1}$$

$$\text{First Moment} = \int_{0.5}^{M} S{\cdot}Nds \tag{2}$$

$$\text{MPS} = \frac{\int_{0.5}^{M} S{\cdot}Nds}{\int_{0.5}^{M} Nds} \tag{3}$$

Where

M = the upper limit of particle size (μm),
N = number of particles in a particular size range, and
S = particle size (μm).

The MPS of the mixed-liquor samples was calculated over the ranges 0.5 to 50 μm, 0.5 to 100 μm, and 0.5 to 200 μm. Larger particles sized from 200 to 500 μm or greater were not considered because larger particles generally settle well and are influenced by flocculation/aggregation or breakup in the secondary clarifiers (Das et al., 1993; Wahlberg et al., 1994). Because flocculation has a short reaction time and typically is not reproduced easily in the laboratory, it is beyond our scope to characterize the largest particles or flocs. Wahlberg et al. (1994) reported that 99% of flocculation was completed within 10 minutes. The smaller particles are of greater interest because they have a higher specific surface

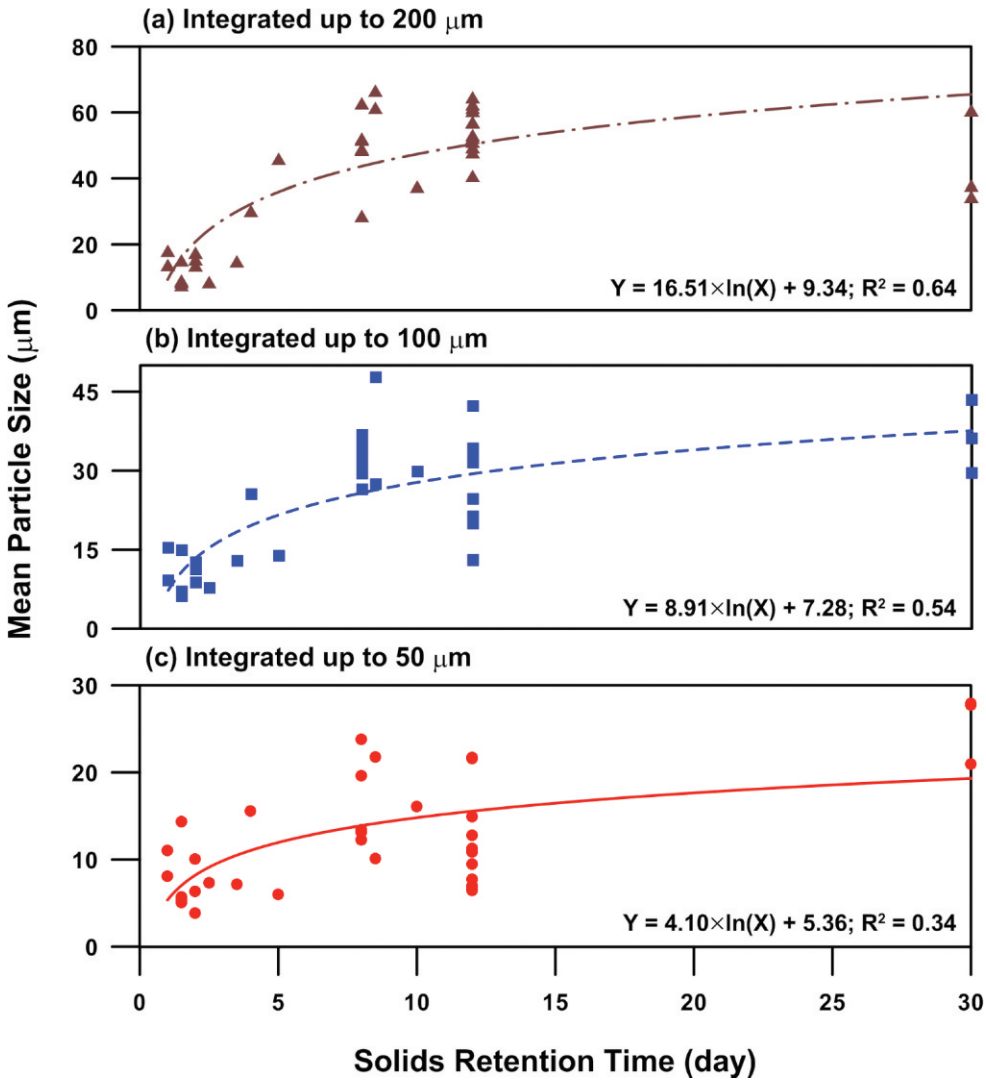

Figure 6—MPSs of all samples plotted against SRTs. The MPSs were calculated by integrating to three cut-off diameters—200, 100, and 50 μm. The trend lines show the logarithm fits of the data.

area and therefore higher concentrations of adsorbed pollutants. The smaller particles are also more difficult to remove in secondary clarifiers and filters.

The MPS is the mean or centroid of PSD and is independent of the total number of particles or mixed-liquor suspended solids (MLSS) concentration, which is an important property, because the tested WWTPs are operating at different SRT and have different MLSS concentrations. Holding time between sample collection and PSD analysis in the laboratory is controlled to 6 hours or less, except for samples collected from treatment plants outside the range of a 1-day traveling distance from the laboratory. Table 1 also shows the average sample holding time for different WWTPs. Four samples collected from plants F, H, I, and K were held for more than 6 hours because of long traveling distance.

Results and Discussion

Particle Size Distribution Repeatability. Figure 2 shows an example of PSD curves of mixed-liquor samples collected from plant D. Because two duplicate samples were collected at each plant at the initial phases of the investigation and each sample was analyzed twice, four PSD curves were generated. The figure shows the specific number of particles as a function of particle size in microns (μm). The specific number of particles (#/μm/mL, or the number of particles over a 1-micron size range per mL of sample) was calculated as the total particle numbers of similar sizes (within a selected range particle size range) per unit volume of sample (Li et al., 2005). The number labeled on top of the curves shows the coefficient of variation of the four measurements at the indicated particle size. The PSD calculated from the spectrums in Figure 2 were similar, and the coefficients of variation of MPSs of the four samples were only 0.03, 0.05, and 0.16 when integrating to 50, 100, and 200 μm, respectively. Because the coefficients of variation were small and the differences among duplicate samples/tests were not significant, the decision was made not to collect and/or analyze replicate samples in the following experiments.

In addition, Figure 2 shows that an extremely large number of particles (more than 5×10^5) are 0.5 μm or smaller; the small particles are best analyzed using laser-light scattering, as

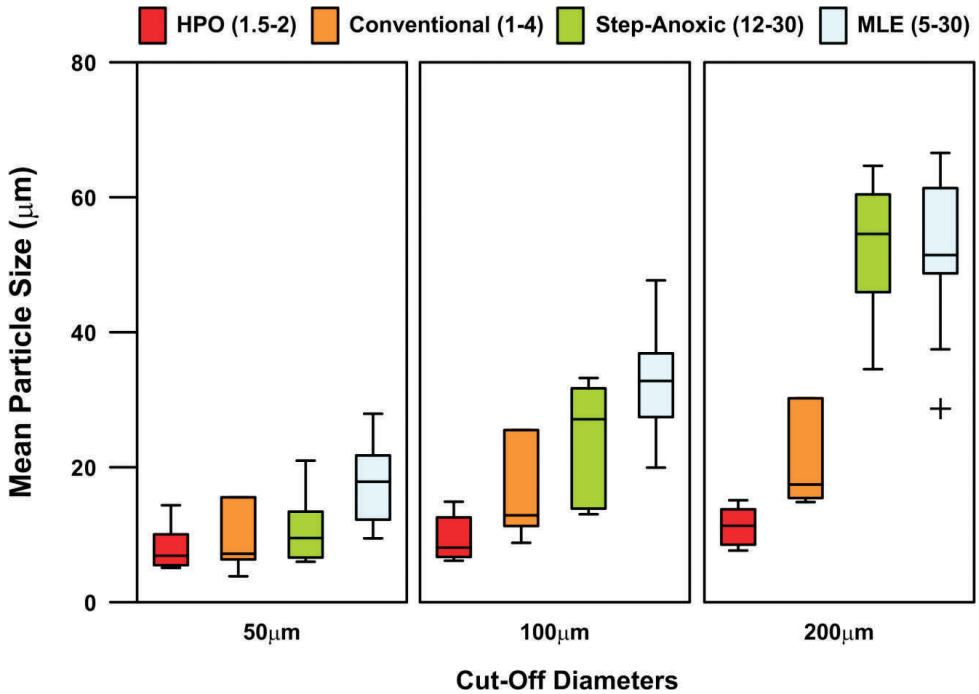

Figure 7—Average and standard deviations of MPSs for different process modifications and SRTs. The four processes were plotted in different colors or shades of gray as the labels shown on top of the figures, and the number labels following the four processes are the range of SRTs. The MPSs were calculated based on three cut-off particle diameters—50, 100, and 200 μm.

opposed to discrete counting, as performed by the Accusizer 780. Particle sizes smaller than 0.5 μm are of importance but are too small to be measured reliably by the Accusizer 780 analyzer.

Figure 3 shows the relationships of MPSs versus the accumulated particle sizes of four WWTPs (plants Q, P, E, and J), which are typical of most samples. The four MPS curves of the tested WWTPs showed similar patterns; for smaller particles, MPS increased with particle sizes and approached a constant after certain ''cut-off'' sizes were reached. Few particles existed above the cut-off size. The four processes showed different maximum MPS diameters. For plants operating at longer SRTs (plant Q and P), the maximum MPS is approximately 55 μm, and the maximum MPSs for short SRT plants (plant E and J) are only 12 and 18 μm. The cut-off particle sizes for representative MPSs are different. In plant J, the MPS approached a maximum value when the particle size integration increased to 50 to 100 μm, but, for plant P, with a long SRT, the critical particle size integration increased to 200 μm. The MPSs for the multiple upper limits of 50, 100, and 200 μm were calculated in this paper, but 200 μm was used for comparisons of low- and high-SRT plants. Figure 3 shows that integrating beyond 50 μm does not bias the MPS for the mixed-liquor samples.

Effect of Holding Time on Mean Particle Size. An investigation to determine the effects of the holding time on MPS was performed to develop a protocol for sampling. The 72-hour tests showed that particles may break up, flocculate, or be re-suspended after holding. Figures 4a and 4b show the ratio of the MPS at given time (MPS_i) over the initial MPS_o at time zero against sample holding time, for the non-step-feed process and step-feed process. Error bars for duplicate measurements are not shown in this figure because they would be too small to observe. Changes in particle sizes during holding time are not consistent and are plant-specific. The average particle sizes of mixed liquor from conventional and MLE processes generally decreased with the sample holding time, but no clear pattern was observed for the step-anoxic processes particle size. With the exception of the step-anoxic plants, the decrease in MPS was no more than 20% after 12 hours of holding time. Figure 4a shows the decreases in MPSs for samples collected from the non-step-feed processes.

Table 2—Average and standard deviations of MPS for different process modifications and SRTs.

			MPS at different cut-off diameters		
Plant	**Process**	**SRT (days)**	**50 μm**	**100 μm**	**200 μm**
A–E	Conventional	1 to 4	8.8±4.6	14.8±6.5	19.2±6.3
F–J	HPO	1.5 to 2	8.1±3.6	9.4±3.6	11.3±3.2
K–T	MLE	5 to 30	16.7±6.8	31.7±9.0	51.1±10.3
U–X	Step-anoxic	12 to 30	11.0±5.1	24.6±8.1	53.1±10.9
Y	TF–Solids Contact	2.5	7.4	7.8	8.5
Z	Oxidation ditch	12	21.6	32.2	53.2

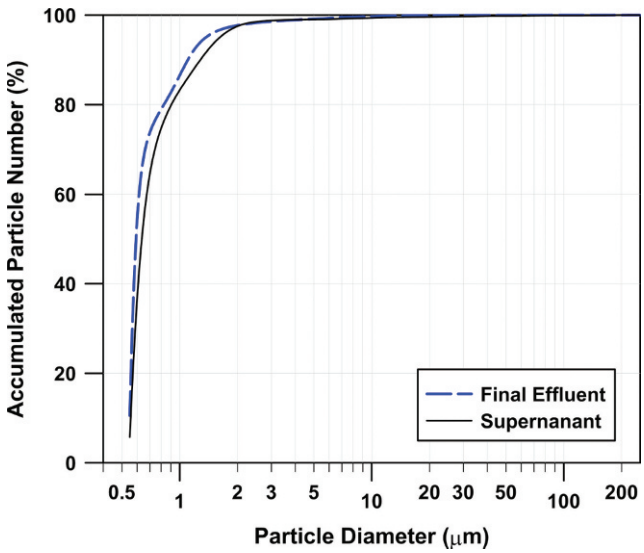

Figure 8—PSD of final effluent and supernatant (samples collected from plant Q).

Most samples decreased no more than 20% after 72 hours; the particles in the step-feed anoxic process are the exception. Figure 4b shows the results of samples collected from the step-anoxic process. The MPS of plant S (step-anoxic) decreased 20%, and the MPS of plant U increased 30% after 3 hours; the other step-anoxic plants showed variable results. Plants U and V were tested more than once, and variable results were observed on both occasions.

It was decided to control the sample holding time to less than 12 hours. Because the particles in the majority processes decreased in size during holding (except step-anoxic processes, which had some apparently random changes in the first 6 hours), the effect of longer holding time or time during transport did not artificially support the hypothesis that larger particles were generated by processes operating at a longer SRT. It will be shown later that particle size is larger for longer-SRT plants, despite any biases that might have occurred as a result of the particle size decrease during holding.

Deflocculation is the most likely explanation for the decline in particle size during holding, in that mixed-liquor solids undergoing endogenous condition for extended periods lost their ability to bioflocculate (Urbain et al., 1993). In the step-anoxic processes, the primary effluent is discharged to the aeration tank at several influent locations along the aeration tanks. Comparing with conventional or MLE processes, which receive the primary effluent at the entrance of the aeration tank, primary influent particles have a shorter contact time to flocculate with the MLSS before exiting the process. Particle size may be unstable in samples from step-anoxic processes, as a result of incomplete flocculation in the aeration tanks; hence, particle growth may occur during the sample holding period.

Particle Size Distribution of Primary Effluent and Mixed-Liquor Solids. Figures 5a and 5b show the PSD of primary effluent samples and mixed-liquor samples. The samples were collected from two treatment plants; plant Q was operating at a long SRT, and plant F was operating at a short SRT. The figures in the top two panels show the accumulated particle number plotted against particle diameter, while the figures in the

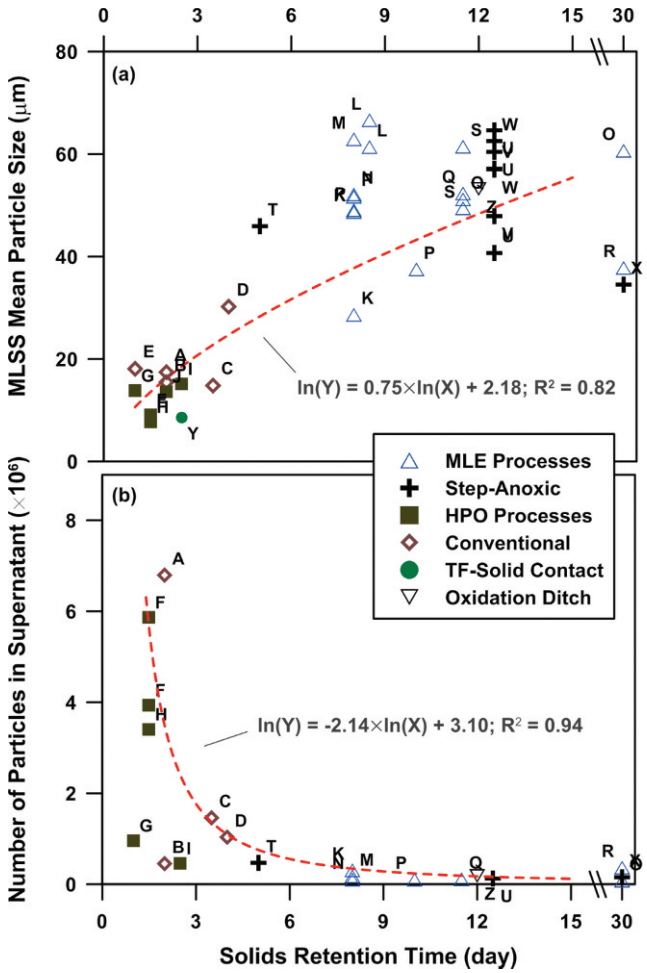

Figure 9—(a) MLSS MPSs of different wastewater treatment processes and SRT, and (b) particle numbers of secondary effluent supernatant from 0.5 to 200 μm after 30 minutes of settling versus SRT. Dashed lines show the power fit of the data from 1 to 15 days SRT, and labels show the keys of the tested wastewater plants. Notice that the x-axis is cut because the MPSs of plants operating at very long SRTs (more than 30 days) show limited increases in MPS.

bottom two panels show the percent changes in particle numbers against particle diameter. The shaded areas show the differences between primary effluent samples and MLSS samples. The number of smaller particles in the mixed liquor decreased, while the number of larger particles increased dramatically. The increase in particle number for larger particles was more significant in the long-SRT plant. For example, for particle sizes ranging from 35 to 60 μm, the particle number in the MLSS was approximately 60 000 times the number in the primary effluent.

Solids Retention Time and Mean Particle Size. Figure 6 shows the relationship of MPS as a function of SRT for all of the sampled WWTPs. The regression curves shown in Figure 6 are the logarithm fits of the data, and the trends of increasing MPSs to SRTs were increased with the cut-off diameters. Table 2 and Figure 7 summarize the averages and standard deviations of MPSs for different operation modifications and SRTs. Increasing

Table 3—Results of particle numbers in mixed-liquor supernatants settled for 30-minutes.

Plant	Process	SRT (days)	MPS cut-off at 200 μm (μm)	Number of particles
A	Conventional	2	17.44	6 790 700
B	Conventional	2	15.44	451 070
C	Conventional	3.5	14.84	1 460 490
D	Conventional	4	30.22	1 033 740
F-1	HPO	1.5	18.12	3 931 850
F-2	HPO	1.5	8.52	5 861 360
G	HPO	1	9.06	953 630
H	HPO	1.5	13.77	3 401 425
I	HPO	1.5	7.66	453 330
K	MLE	8	15.11	309 855
M	MLE	8	13.59	173 210
N	MLE	8	48.73	101 805
O	MLE	30	28.65	73 725
P	MLE	10	66.57	105 605
Q	MLE	12	61.36	109 720
R	MLE	30	62.86	363 440
T	Step-anoxic	5	52.14	466 900
U	Step-anoxic	12	60.65	128 735
X	Step-anoxic	30	51.72	151 680
Z	Oxidation ditch	12	49.04	182 835

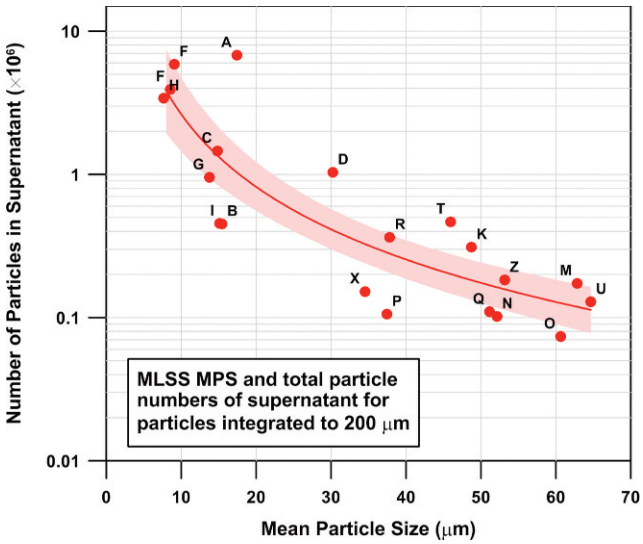

Figure 10—Relationship of particle numbers of secondary effluent supernatant and mean MLSS MPS. The curve shows the power fit of the data, and the shaded area shows the 95% confidence interval. Notice that the y-axis is in logarithm scale.

particle sizes with SRTs were observed from three cut-off particle sizes (50, 100, and 200 μm). The MPSs for conventional ASP and HPO processes operating at SRTs ranging from 1 to 4 days were mostly less than 20 μm, and, for MLE and step-anoxic processes with SRTs more than 8 days, the MPSs were mostly greater than 20 μm. The MPS depends on the range of integration, and the trends in MPS versus SRT are all similar, but the trend is probably most distinct using 200 μm as a cut-off limit. The WWTPs operating at very long SRT (plants O and R) have large MPSs, but the particle size is approximately comparable with those collected from WWTPs with 8- to 12-day SRTs, suggesting that there might be a maximum achievable MPS.

The MPS analysis reveals that the cut-off points may not be a particularly sensitive parameter, because the MPS is weighted by particle number, but not particle mass. Fewer particles exist above 200 μm, which minimizes its effect on the MPS calculation (Figure 3). Additionally, particles larger than 200 μm probably are related more to the amount and type of flocculation that occurs just before counting. The particle counter may deflocculate large particles during the tests also.

Results of Clarification Tests. The other hypothesis of this research is that the larger particle size of the MLSS is associated with fewer effluent particles in the settled mixed-liquor and process effluent. The beaker settling test described previously was used to simulate clarifier performance. The number of particles in the supernatant of quiescent samples was measured at 0.5, 1, and 2 hours, roughly spanning the retention time of clarifiers used in secondary treatment. The results from the three designed settling times were virtually identical, and the results of the 0.5-hour (30-minute) settling time were chosen for comparison. Because the clarification experiments were designed to evaluate the settling properties, it is essential that the settling behavior of the MLSS samples in the laboratory represents what happens in the secondary clarifiers, at least for well-designed and operated clarifiers. Figure 8 shows the PSD of the supernatant and the secondary effluent collected from plant Q, and the result is typical of the other plants, which are not shown. The two curves virtually overlap, suggesting that the settling tests should be sufficiently representative of the settling behavior of well-operating secondary clarifiers.

Figures 9a and 9b show the MPS (cut-off at 200 μm) of all 37 measurements (26 plants, some sampled more than once, at different times) and the relationship of the particle number in the biosolids supernatant against SRTs, respectively. Different WWTPs or processes are distinguished with labels, and the dashed curves show the power fits of measurements at SRTs from 1 to 15 days. The MPS increases with SRT and follows the power function, except for plants operating at an extremely long SRT (30 days). The MPSs of plants operating at a 30-day SRT are approximately identical to plants operating at a 12-day SRT.

Figure 9b and Table 3 shows the mean particle numbers of different processes measured from the sludge supernatants after 30 minutes of settling. The decrease of particle number in supernatant follows a power function with increasing SRT, except for plants G, B, and I (low-SRT plants), in which only a few particles were measured. The causes of this low particle number are plant-specific. Plants G and used HPO processes, and plant B used a conventional ASP. Consistently good SVI for the mixed-liquor samples was recorded at plant I (approximately 67 mL/g), but the SVI for plant G was much higher (approximately 133 to 323 mL/g). Nevertheless, all plants operating at SRTs higher than 5 days showed a low particle number in the supernatant, which illustrates the benefits of long SRT operation.

Total suspended solids (TSS) data of the secondary effluents were not available during the testing periods, but were within the typical ranges. The effluent TSS concentration in plant F (HPO process, 1.5-day SRT) was approximately 20 to 45 mg/L and was 5 to 10 mg/L in plant P (MLE process, 8-day SRT). The effluent TSS concentration in plant U using the step-anoxic process was

5 to 15 mg/L. The results generally agree with our observations of particle numbers in the supernatants.

Figure 10 shows the relationship of particle number in supernatant and the MPS of the MLSS. Few particles were measured in the supernatant of mixed-liquor samples with a high MPS. The results of PSD analysis demonstrated the relationship between larger particles and better settleability for MLSS, and this result occurs irrespective of the cut-off diameters for the MPS calculation (0.5 μm to 50, 100, and 200 μm). The PSD analysis can be applicable in predicting the effluent quality of secondary clarification.

Conclusions

Suspended solids from WWTPs conventionally have been characterized by simpler techniques, such as TSS, volatile suspended solids (VSS), or turbidity. This work has developed a new technique using particle size analysis that can be used to evaluate the conditions of the biosolids. Differences in operation can be quantified and used to justify plant-operating strategies. The key findings of this investigation are summarized as follows:

(1) This paper introduces the parameter mean particle size, or MPS, to characterize MLSS biosolids; MPS is calculated by integrating the average particle size over selected diameter ranges. The MPS of three ''cut-off'' diameters (i.e., 0.5 to 50, 100, or 200 μm) were evaluated and used to distinguish the differences of PSD for different process modifications and SRTs. Integration to 200 μm was most representative in differentiating longer SRT treatment plants.
(2) A series of 72-hour tests showed that particle size can change with sample holding time. The time between sample collection and analysis should be minimized, to reduce the effects of deflocculation. Significant changes in particle size were observed for most mixed-liquor samples after 12 hours of holding. For the same holding period, samples collected from step-anoxic processes showed much higher variations than activated sludge or MLE processes.
(3) PSD analysis shows that particle numbers in supernatants decrease with the increase in particle size of biosolids (MPS), which typically occurs at WWTPs operating at higher SRTs (>5 to 8 days). These findings strengthen the results from previous studies and can be used as an additional index to evaluate the properties of biosolids.
(4) The reduced numbers of particles in effluents from longer SRT processes provide additional support for longer SRT operation, as noted in previous work (Leu et al., 2011; Rosso and Stenstrom, 2005; Rosso et al., 2005).

Credits

The authors thank the various treatment plant managers and operators for their assistance in obtaining samples.

Submitted for publication October 4, 2010; revised manuscript submitted February 21, 2011; accepted for publication February 28, 2011.

References

Barbusiński, K.; Kościelniak, H. (1995) Influence of Substrate Loading Intensity on Floc Size in Activated Sludge Process. *Water Res.*, **29,** 1703–1710.

Bentzen, T. R.; Larsen, T. (2009) Heavy Metal and PAH Concentrations in Highway Runoff Deposits Fractionated on Settling Velocities. *J. Environ. Eng.*, **135,** 1244–1247.

Bisogni Jr, J. J.; Lawrence, A. W. (1971) Relationship Between Biological Solids Retention Time and Settling Characteristics of Activated Sludge. *Water Res.*, **5,** 753–763.

Bolong, N.; Ismail, A. F.; Salim, M. R.; Matsuura, T. (2009) A Review of the Effects of Emerging Contaminants in Wastewater and Options for their Removal. *Desalination*, **239** (1–3), 229–246.

Bourgeous, K.; Narayanan, B.; Deis, G. (2003) Particle Size Distribution Testing as a Diagnostic Tool for Optimizing Filtration and UV Disinfection Systems. *Proceedings of the 76th Annual Water Environment Federation Technical Exposition and Conference,* Los Angeles, California, Oct. 11–15; Water Environment Federation: Alexandria, Virginia.

Chao, A. C.; Keinath, T. M. (1979) Influence of Three Factors on Clarification in the Activated Sludge Process. *Water Res.*, **13,** 1213–1223.

Das, D.; Keinath, T. M.; Parker, D. S.; Wahlberg, E. J. (1993) Floc Breakup in Activated Sludge Plants. *Water Environ. Res.*, **65,** 138–145.

Han, Y. H.; Lau, S.-L.; Kayhanian, M.; Stenstrom, M. K. (2006) Correlation Analysis Among Highway Stormwater Pollutants and Characteristics. *Water Sci. Technol.*, **53,** 235–243.

Jenkins, D.; Richard, M. G.; Daigger, G. T. (2004) *Manual on the Causes and Control of Activated Sludge Bulking, Foaming, and Other Solids Separation Problems,* 3rd ed.; IWA Publishing: London, United Kingdom.

Knocke, W. R.; Zentkovich, T. L. (1986) Effects of Mean Cell Residence Time and Particle Size Distribution on Activated Sludge Vacuum Dewatering Characteristics. *J. Water Pollut. Control Fed.*, **58,** 1118–1123.

Leu, S-Y.; Chan, L. C.; Stenstrom, M. K. (2011) Toward Long SRT of Activated Sludge Processes: Benefits in Energy Saving, Effluent Quality, and Stability. *Water Environ. Res.* (in press).

Levenspiel, O. (1967) *Chemical Reaction Engineering,* 1st ed.; John Wiley & Sons: New York.

Li, Y. X.; Lau, S.-L.; Kayhanian, M.; Stenstrom, M. K. (2005) Particle Size Distribution in Highway Runoff. *J. Environ. Eng.*, **131,** 1267–1276.

Liu, H.; Sun, L.; Wang, Y.; Xia, S.; Le, L. (2009) Application of Particle-Size Analysis in Coagulation/Flocculation for Reclamation of a Secondary Effluent. *Water Sci. Technol.*, **60,** 1455–1463.

Metcalf & Eddy (2003) *Wastewater Engineering: Treatment and Reuse*, Tchobanoglous, G., Burton, F. L., Stensel, H. D. (Eds.); McGraw-Hill: New York.

Palm, J. C.; Jenkins, D.; Parker, D. (1980) Relationship Between Organic Loading, Dissolved Oxygen Concentration and Sludge Settleability in the Completely-Mixed Activated Sludge Process. *J. Water Pollut. Control Fed.*, **52,** 2483–2506.

Petrovic, M.; Gonzalez, S.; Barcelo, D. (2003) Analysis and Removal of Emerging Contaminants in Wastewater and Drinking Water. *Trends Anal. Chem.*, **22,** 685–696.

Rosso, D.; Iranpour, R.; Stenstrom, M. K. (2005) Fifteen Years of Off-Gas Transfer Efficiency Measurements on Fine Pore Aerators: Key Role of Sludge Age and Normalized Air Flux, *Water Environ. Res.*, **77,** 266–273.

Rosso, D.; Stenstrom, M. K. (2005) Comparative Economic Analysis of the Impacts of Mean Cell Retention Time and Denitrification on Aeration Systems. *Water Res.*, **39,** 3773–3780.

Schorer, M. (1997) Pollutant and Organic Matter Content in Sediment Particle Size Fractions. *Freshwater Contam.*, **243** (4–5), 59–67.

Urbain, V.; Block, J. C.; Manem, J. (1993) Bioflocculation in Activated Sludge: An Analytic Approach. *Water Res.*, **27,** 829–838.

Wahlberg, E. J.; Keinath, T. M.; Parker, D. S. (1994) Influence of Activated Sludge Flocculation Time on Secondary Clarification. *Water Environ. Res.*, **66,** 779–786.

Wilén, B.-M.; Balmér, P. (1999) The Effect of Dissolved Oxygen Concentration on the Structure, Size and Size Distribution of Activated Sludge Flocs. *Water Res.*, **33,** 391–400.