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Journal of Hazardous Materials B67 (1999) 95–109

Journal of Hazardous Materials

Factors influencing suspended solids concentrations in activated sludge settling tanks

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Received 1 September 1998; received in revised form 8 September 1998; accepted 10 February 1999

Abstract

A significant fraction of the total mass of sludge in an activated sludge process may be in the settling tanks if the sludge has a high sludge volume index (SVI) or when a hydraulic overload occurs during a rainstorm. Under those conditions, an accurate estimate of the amount of sludge in the settling tanks is needed in order to calculate the mean cell residence time or to determine the capacity of the settling tanks to store sludge. Determination of the amount of sludge in the settling tanks requires estimation of the average concentration of suspended solids in the layer of sludge (X_{SB}) in the bottom of the settling tanks. A widely used reference recommends averaging the concentrations of suspended solids in the mixed liquor (X) and in the underflow (X_u) from the settling tanks ($X_{SB} = 0.5\{X + X_u\}$). This method does not take into consideration other pertinent information available to an operator. This is a report of a field study which had the objective of developing a more accurate method for estimation of the X_{SB} in the bottom of the settling tanks. By correlation analysis, it was found that only 44% of the variation in the measured X_{SB} is related to sum of X and X_u. X_{SB} is also influenced by the SVI, the zone settling velocity at X and the overflow and underflow rates of the settling tanks. The method of averaging X and X_u tends to overestimate the X_{SB}. A new empirical estimation technique for X_{SB} was developed. The estimation technique uses dimensionless ratios; i.e., the ratio of X_{SB} to X_u, the ratio of the overflow rate to the sum of the underflow rate and the initial settling velocity of the mixed liquor and sludge compaction expressed as a ratio (dimensionless SVI). The empirical model is compared with the method of averaging X and X_u for the entire range of sludge depths in the settling tanks and for SVI values between 100 and 300 ml/g. Since the empirical model uses dimensionless ratios, the regression parameters are also dimensionless and the model can be

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PII: S0304-3894(99)00028-X

readily adopted for other activated sludge processes. A simplified version of the empirical model provides an estimation of X_{SB} as a function of X, X_u and SV_f and can be used by an operator when flow conditions are normal.

Keywords: Activated sludge processes; Settling tanks; Sludge blanket depth (SBD)

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1. Introduction

The total mass of sludge solids in an activated sludge process (M_T) includes the sludge in the settling tanks (M_s) as well as the sludge in the aeration tanks (M_a):

$$M_T = M_a + M_s. \tag{1}$$

M_a is easily calculated from:

$$M_a = V_a X f, \tag{2}$$

where V_a is the volume of the aeration tanks (known from the plant design), X is the mixed liquor suspended solids (normally measured once a day or more frequently), and f is a unit conversion factor ($f = 0.001$ kg/g when V_a is in m^3 and X is in g/m^3). The amount of sludge in the settling tanks [1] can be calculated from:

$$M_s = V_s X_{SB} f, \tag{3}$$

where V_s is the volume of the layer of sludge in the bottom of the settling tanks and X_{SB} is the average suspended solids concentration in that layer.

Some of the design and operating parameters on an activated sludge process (e.g. F/M ratio) depend upon M_a but others are more properly related to M_T. For example, the mean cell residence time, θ_x, should be based on M_T to give an accurate estimation of the average amount of time that a microbial cell spends in the process. It is often assumed that M_s will be negligible compared with M_a and the calculation of θ_x is based on M_a rather than M_T. However, when the sludge volume index (SVI) is high, M_s can be a significant fraction (up to 40%) of M_T [2] and neglecting M_s in the calculation of θ_x can mislead the operator.

A diagram of an activated sludge settling tank with the mass flows of suspended solids indicated is presented in Fig. 1. In the United States, the layer of sludge in the bottom of the settling tanks is called a ‘sludge blanket’ and X_{SB} is the ‘sludge blanket suspended solids’.

The sludge blanket depth is indicated by SBD and $V_s = (\mathrm{SBD})(A_s)$ where A_s is the area of the settling tanks. J_m is the mass flow of mixed liquor suspended solids flow, J_u is the mass flow of suspended solids out of the bottom of the settling tanks and J_e is the mass flow of suspended solids in the effluent. It is widely recognized that clarification of the effluent so that J_e is small and thickening of the sludge so that J_u is almost as large as J_m are two important functions of activated sludge settling tanks and these functions have been studied by many investigators.

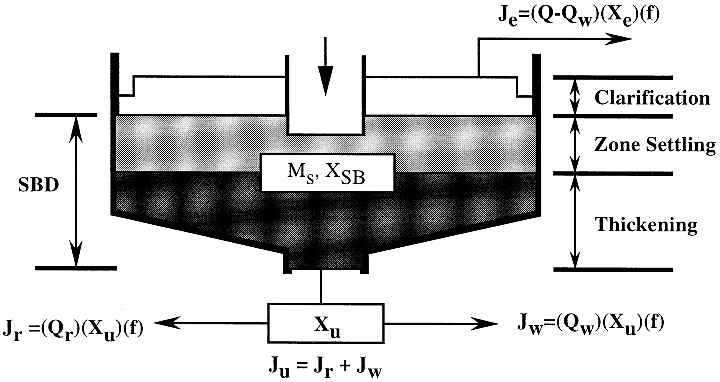

Fig. 1. Diagram of an up-flow settling tanks with identification of mass flows of suspended solids, the sludge blanket depth and zones in the settling tank.

A mass balance of the suspended solids into and out of the settling tank can be written as:

$$\frac{\mathrm{d}M_s}{\mathrm{d}t} = \{(Q+Q_r)(X) - (Q_r+Q_w)(X_u) - (Q-Q_w)(X_e)\}(f). \tag{4}$$

The terms are defined in Fig. 1 and in Appendix A. In a municipal wastewater treatment plant, Q may increase to two or three times greater than the normal dry weather flow during a rainstorm. When Q is very high (hydraulic overload), J_u will not carry sludge solids out of the settling tanks as fast as they are brought in with J_m and $\mathrm{d}M_s/\mathrm{d}t > 0$. For a finite period of time, Δt, during the hydraulic overload, $\Delta M_s = (J_m - J_u)\Delta t$ has to be stored in the settling tanks until the rainstorm is over and the sludge can be pumped back to the aeration tanks. The total solids storage in the settling tanks at $t = t$ from $t = 0$ during storm flow conditions [3] can be evaluated from:

$$M_{st=t} = M_{st=0} + \sum_{t=1}^{t=t} (J_m - J_u - J_e)(\Delta t). \tag{5}$$

The solids storage function of activated sludge settling tanks has been studied by a few investigators [4,5]. There is a maximum limit on M_s which depends upon the surface area and depth of the settling tank and on the X_{SB}. Knowledge of this maximum limit is needed to evaluate how well the settling tanks functions to store sludge during hydraulic overloads.

Other investigators have studied solid concentrations in settling tanks but were addressing the thickening function rather than the solids storage function. Pflanz [6], in an experiment at Celle, measured suspended solids concentrations at various depths and identified the three zones shown in Fig. 1 as a clarification zone with less than 50 mg/l suspended solids, a transition zone with a concentrations between 100 and 1000 mg/l and a thickening zone with higher suspended solids concentration. Vitasovic [4] developed a model of thickening which predicts vertical profiles of the solids concentrations in the sludge blanket. Takacs et al. [7] tried to explain the dynamics of the thickening process using the same parameters as Pflanz [6]. Samstag et al. [8] used a numerical model of stratified flow to illustrate density flow effects.

However, none of these investigators proposed a technique for estimating X_{SB}. The only currently documented technique is averaging the mixed liquor suspended solids (X) and the underflow suspended solids (X_u) concentrations [9]:

$$X_{SB} = \frac{(X + X_u)}{2}. \tag{6}$$

Eq. (6) uses only a small part of the information usually available to an operator and does not take into consideration the effects of either the sludge settling characteristics or of the operation of the settling tanks on X_{SB}.

We undertook a field study to develop a method for estimating X_{SB} which uses information in addition to X and X_u. We investigated parameters which a plant operator can readily ascertain including the activated sludge settling and compaction characteristics and the hydraulic loading conditions of the settling tanks.

2. Methods and materials

The data were obtained from a regional wastewater treatment plant in Chester, PA which is rated to treat a flow of 166 540 m^3/d. The activated sludge process in this plant has four mechanically aerated aeration tanks (total aeration tank volume = 37 850 m^3) and four circular, center feed, up-flow, settling tanks. The mixed liquor is divided equally among the four settling tanks and flows into each through a center stilling well. The thickened sludge is siphoned from the bottom of each tank at six different locations on a rotating arm. The total area of settling tanks is 4930 m^2 and the side water depth is 4.57 m.

Samples for measurement of X, X_e, X_u and X_{SB} were collected once or twice a week for the period from September 1992 through August 1994. Suspended solids determinations were performed in duplicate on each sample following Method 213C of Standard Methods for the Examination of Water and Wastewater [10].

Settling tests on the mixed liquor were performed in 1000 ml graduated cylinders which were stirred at 1 rpm to minimize the wall effects [10]. Four sets of settling tests were performed for each of the mixed liquor samples and the results were averaged. After 30 min, the sludge volume was recorded as a fraction (SV_f) of the initial volume and well as the absolute volume in ml. Also, the initial settling velocity (ISV) of the mixed liquor suspended solids was calculated from a linear regression on the initial parts of the settling curves.

The sludge blanket depths (SBD) were measured at the same times that the samples for determination of X_{SB} were collected. A number of devices for sampling the sludge blanket have been described previously [11]. We used a simple tube type device, illustrated in Fig. 2, for collecting the solids samples and locating the top of the sludge blanket. As the tube is lowered slowly into settling tank, the water pressure keeps the valve open allowing the sludge to enter the tube with a minimum of disturbance. This sampling device is the same as those used by the operators at the plant studied for

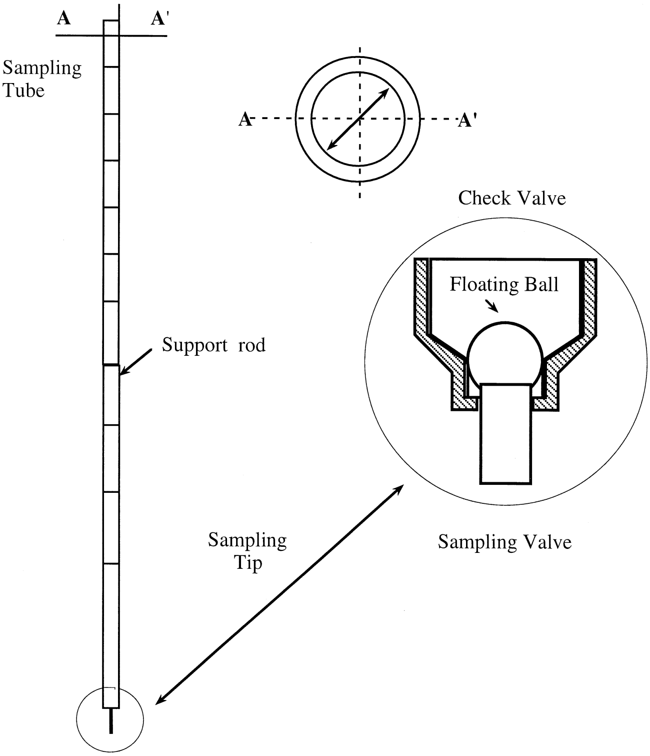

Fig. 2. Diagram of the apparatus used for sampling the sludge blanket.

measuring the SBD in each tank every 2 h and is readily available to operators at other plants.

When a sample of the sludge blanket is withdrawn from a settling tank, the height of the sludge/water interface can be determined visually. The depth of sludge blanket is determined by subtracting the depth of the top of the sludge blanket from the side water depth of the settling tanks. On each sampling trip, six samples of the sludge blanket were obtained at equally spaced intervals from the center to the periphery of the settling tank. Each sample included a section from the top to bottom of the sludge blanket and had a volume of about 2000 ml. Duplicate determinations of the suspended solids concentration of each sample were made and the X_{SB} was calculated by multiplying by the tank depth divided by the measured SBD.

3. Results and discussion

Data from the 56 sampling trips are presented in Table 1. The mixed liquor suspended solids concentration varied between 1315 and 2715 mg/l and the underflow suspended solids concentration varied between 4215 and 7190 mg/l. The SVI was often

Table 1
The results of 56 sampling trips between September 1992 and August 1994

No.	Date	X (mg/l)	X_{u} (mg/l)	Q (m^3/d)	SVI (ml/g)	ISV (cm/min)	Q_{r} (m^3/d)	X_{SB} (mg/l)	SBD (m)
1	9/16/92	1700	5460	123 353	197	2.27	58 213	1612	2.26
2	9/25/92	1775	5960	132 475	185	2.30	53 369	1940	2.20
3	10/2/92	1930	5855	118 054	192	1.98	51 703	1616	1.49
4	10/9/92	1965	5645	128 235	153	2.39	64 345	1940	1.83
5	10/16/92	1810	5385	124 905	144	3.05	61 317	2628	1.16
6	10/30/92	1980	6040	113 928	141	2.83	58 668	2843	1.19
7	11/6/92	2010	6016	134 746	131	3.47	62 453	3103	1.31
8	11/13/92	1483	4985	160 711	157	3.78	68 130	2267	1.52
9	11/14/92	1615	4915	130 923	150	3.16	55 261	2035	0.98
10	11/19/92	1600	5054	119 984	153	3.05	54 504	2829	0.76
11	11/20/92	1630	4235	123 391	157	2.84	59 803	1878	0.95
12	12/4/92	1610	5310	117 335	161	2.95	61 317	2483	1.19
13	12/11/92	1315	5775	230 772	158	3.50	51 855	1900	3.32
14	12/17/92	1930	6790	161 620	114	4.02	66 238	3815	0.95
15	12/22/92	1785	5800	123 353	112	4.25	62 263	3320	0.52
16	12/24/92	1965	5460	87 055	109	4.20	38 607	3273	0.46
17	12/29/92	1920	5515	122 218	107	4.30	64 345	4172	0.73
18	1/15/93	1960	5905	124 527	110	4.06	58 289	3587	0.77
19	1/22/93	1720	5415	153 293	116	4.30	74 943	3392	0.69
20	1/27/93	1770	5735	129 069	121	4.30	62 074	3044	1.10
21	1/29/93	1775	5715	125 283	110	4.11	57 911	3284	0.72
22	2/3/93	1550	5140	132 096	116	4.70	62 831	3045	0.70
23	2/5/93	1550	4835	135 124	121	4.56	62 074	3640	0.79
24	2/12/93	1650	5285	149 508	133	4.52	73 429	3467	0.94
25	2/19/93	1715	5640	136 639	128	4.14	61 696	3696	1.07
26	3/3/94	2185	6645	164 383	105	4.23	90 840	3554	1.59
27	3/9/94	2210	6350	152 536	100	4.80	90 840	4038	1.19
28	3/10/94	1170	6340	291 456	111	6.21	90 840	3223	2.71
29	3/11/94	2375	6485	150 643	93	4.23	90 840	3800	1.34
30	3/17/94	2345	7120	134 027	98	4.32	55 639	4118	1.09
31	3/22/94	2290	7055	161 620	100	4.32	83 270	4099	1.70
32	3/24/94	2580	6915	127 276	93	3.56	63 588	3587	1.62
33	3/28/94	2370	6495	153 898	93	4.32	90 840	3997	1.83
34	3/29/94	2435	6310	166 805	86	4.32	90 840	4058	1.98
35	4/5/94	2305	6425	147 615	89	4.41	90 840	4173	1.28
36	4/6/94	2135	5935	148 334	98	4.41	90 840	3369	1.37
37	4/12/94	2490	6330	136 374	92	4.32	83 270	4234	1.29
38	4/14/94	2500	6645	155 147	96	4.23	85 541	4096	1.40
39	4/19/94	2500	7190	141 673	108	3.78	80 242	4408	1.71
40	4/21/94	2605	6555	118 656	92	3.08	60 560	3845	1.28
41	4/26/94	2625	7005	121 007	95	2.95	58 137	4432	1.49
42	4/29/94	2715	6800	143 830	111	2.77	66 199	3342	1.98
43	5/3/94	2420	6575	136 638	99	4.05	77 668	4291	1.56
44	5/5/94	2340	6985	134 368	98	3.96	67 183	4457	1.13
45	5/13/94	2270	6100	116 957	106	4.05	56 131	4387	0.95
46	5/17/94	2220	6135	137 017	108	4.05	68 508	3512	1.22
47	5/27/94	2285	6385	162 755	101	3.78	81 377	2915	1.13
48	6/1/94	2220	6650	140 045	99	4.03	70 022	3475	1.04

Table 1 (continued)

No.	Date	X (mg/l)	X_u (mg/l)	Q (m^3/d)	SVI (ml/g)	ISV (cm/min)	Q_r (m^3/d)	X_{SB} (mg/l)	SBD (m)
49	6/3/94	2310	6060	162755	97	3.88	90840	3065	1.01
50	6/8/94	2115	6215	140045	99	4.21	51788	3442	0.91
51	6/21/94	1940	5090	105980	124	3.64	40272	2932	0.76
52	6/24/94	1910	5355	105980	136	3.87	40272	2952	1.21
53	6/28/94	2095	5765	109765	124	3.04	43906	3726	1.37
54	7/11/94	2050	5225	117032	117	3.51	50870	3302	0.76
55	7/19/94	2180	5875	149659	106	4.50	90840	3582	1.16
56	7/27/94	2070	5830	128690	87	4.86	64345	4151	1.01

high (bulking sludge). The relatively wide range of variation in the SVI and the initial settling velocity provided the data needed for determining the effects of sludge settling characteristics on X_{SB}.

The return sludge flow rate was adjusted by the plant operators every 2 h and was usually maintained between 40 and 50% of the influent flow. During rainstorms when Q was large, Q_r was limited by the capacity of the return sludge pumps to 102 000 m^3/d and Q_r/Q decreased as Q increased.

3.1. Sampling of sludge blanket suspended solids

Estimation of the amount of suspended solids in the settling tanks requires measurement of both the sludge blanket depth (SBD) and the average suspended solids concentration in the sludge blanket (X_{SB}). At the start of this investigation,we did not have any information on the reliability of the measuring tube device for collecting suspended solids samples and carried out short-term studies to make sure that we were obtaining the samples which would give the data needed.

In order to check for sampling disturbances when the transparent tube is used, the solids profile in the sludge layer in the sampling tube was determined three times and the results are presented in Fig. 3. These results show that the sludge layer in a settling tank can be sampled using the tube type sampler without causing back-mixing of sludge solids. It would be possible to obtain vertical concentrations profiles if that information was desired.

The diameter of each settling tank sampled was approximately 10 m and we considered the possibility that the SBD might vary from the center to the periphery of a tank. During each sampling trip, six SBD measurements were obtained at equally spaced intervals from the center to periphery of the settling tank. The average SBD of the six different location is plotted in Fig. 4 and this shows that there is no significant difference between the average SBD and the SBD measured at halfway between the center and periphery of the settling tank.

Other investigators literature have measured vertical profiles of suspended solids concentrations in settling tanks [6,8]. The method used by these other investigators was

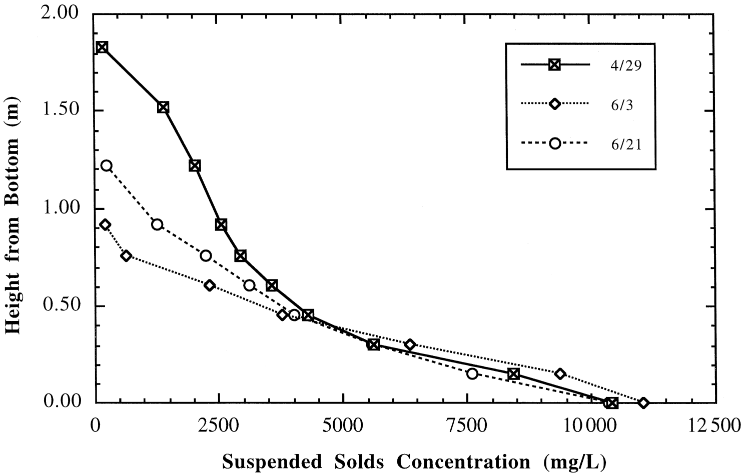

Fig. 3. Vertical solids profiles obtained from the sludge blanket sampler.

to draw samples from different depths in the tank. This approach is not feasible method for plant operation because of sampling time and effort and the large number of suspended solids determinations required. Operators could use the transparent tube sampling device to obtain samples for measurement of the X_{SB}.

In this study, six samples from the sludge blanket were collected at equally spaced intervals between the center and periphery of the settling tanks. Fig. 5 shows a plot of the average X_{SB} values from the six different sampling locations vs. the X_{SB} measured

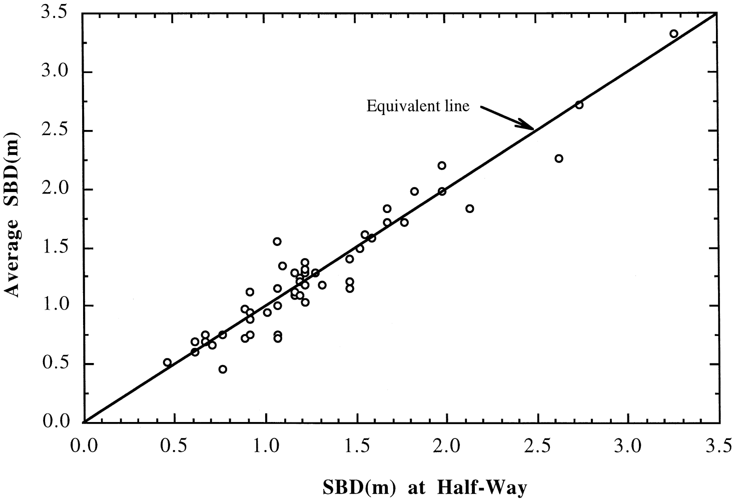

Fig. 4. Comparison between SBD measured at halfway and average SBD.

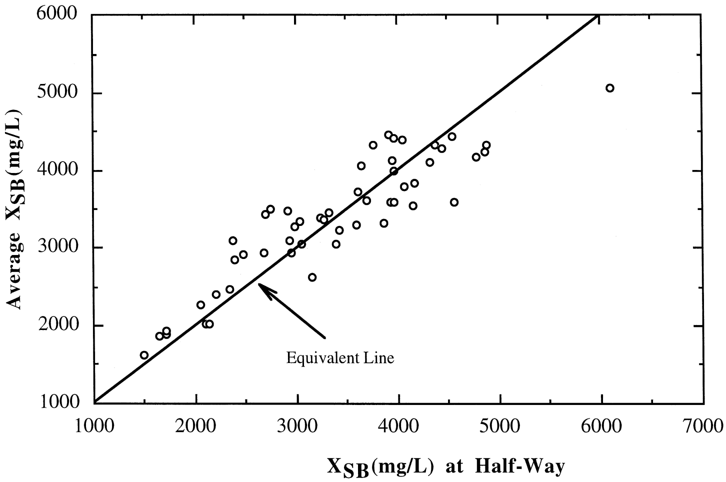

Fig. 5. Comparison between X_{SB} measured at halfway and average X_{SB}.

halfway between the center and periphery. This indicates that sampling at the halfway point gives a reasonable approximation of the average X_{SB} for the entire settling tanks.

3.2. Averaging method for estimating X_{SB}

Even with the transparent tube sampling device, the sampling and analytical effort required for accurate measurement of X_{SB} is usually more than the operating personnel at a wastewater treatment plant can afford. In the past, the operating personnel at the plant which we used in this investigation have estimated the X_{SB} as the average of the X and the X_u (Eq. (6)).

The usefulness of this approach for estimating the X_{SB} was tested by a linear regression of the measured X_{SB} vs. the sum of X and X_u for the data in Table 1. The results of this regression are presented in Fig. 6.

Clearly, there is a correlation between $(X + X_u)$ and X_{SB}, but the correlation coefficient is 0.44 which indicates that only 44% of variation in the measured X_{SB} is related to the sum of X and X_u. The slope of regression line is 0.53, which is very close to the 0.5 used in Eq. (6), but the intersection is -846 mg/l, which indicates that the average method tends to overestimate the X_{SB} in the settling tanks.

3.3. Development of new estimation technique

Correlations between X_{SB} and X and between X_{SB} and X_u demonstrated that both X and X_u influence the value of X_{SB} but did not explain all of the variation in X_{SB}. One hypothetical limit to the thickening process can be thought of as X_{SB} being equal to X_u when the SBD is zero. To accommodate this hypothetical limit, we decided to correlate the ratio of X_{SB}/X_u with other variables representing the flow conditions in the settling tank and the sludge settling and compaction characteristics. We decided also

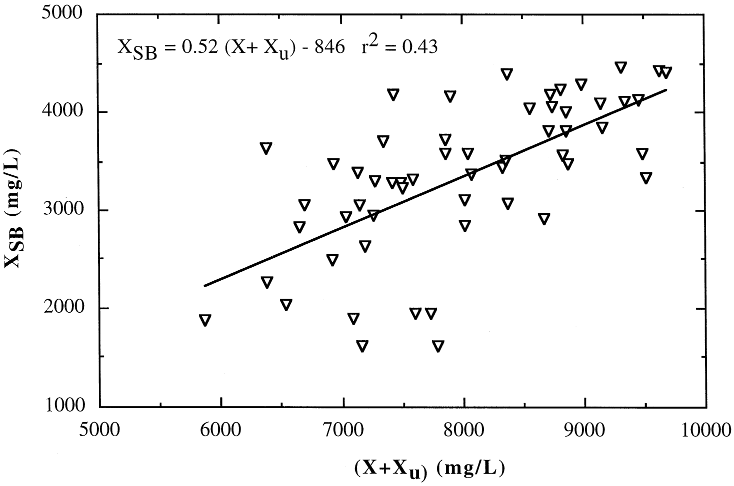

Fig. 6. Linear regression of average method.

to use dimensionless ratios for the other variables so that the regression parameters would not have dimensions.

By considering several variables which a plant operator can readily evaluate, the following functional relationship may be written:

$$\frac{X_{\mathrm{SB}}}{X_{\mathrm{u}}} = \phi[v, u, \mathrm{ISV}, X_{\mathrm{i}}, \mathrm{SV_f}], \tag{7}$$

where v is overflow rate over the settling tank (Q/A_s), u is the underflow rate (Q_r/A_s), ISV is the initial zone settling velocity of mixed liquor suspended solids [m/d], $\mathrm{SV_f}$ = sludge volume fraction after 30 min settling in an 1 l graduated cylinder [l/l], and X_i is the mixed liquor suspended solids in weight per unit weight [kg/kg]. If the density of the mixed liquor is not significantly different from 1 g/ml, then X_i is X divided by 10^6 mg/kg.

Several trials of regression and correlation resulted in the finding that the logarithm of $X_{\mathrm{SB}}/X_{\mathrm{u}}$ was more closely correlated with the other variables than the simple ratio and that the other variables could be efficiently expressed as two ratios, $v/(\mathrm{ISV}+u)$ and $\mathrm{SV_f}/X_i$:

$$\ln\left[\frac{X_{\mathrm{SB}}}{X_{\mathrm{u}}}\right] = \psi\left[\frac{v}{\mathrm{ISV}+u}, \frac{\mathrm{SV_f}}{X_{\mathrm{i}}}\right]. \tag{8}$$

The velocity ratio between $v/(\mathrm{ISV}+u)$ represents the effects of hydrodynamic forces on the sludge layer in the settling tanks as well as the settling characteristics of the sludge and the ratio of $\mathrm{SV_f}$ to X_i is primarily a measure of how well the solids compact; i.e., how high a concentration is reached in 30 min settling and compaction in a graduated cylinder. It should be noted that both the 30 min settled volume and the mixed liquor suspended solids concentrations are expressed as dimensionless ratio, $SVI = SV_f/X_i$.

Almost any mathematical function can be expressed as a power series. In this case, only the first terms are considered for dimensional homogeneity. Eq. (8) is altered to:

$$\ln\left[\frac{X_{SB}}{X_u}\right] = c\left[\left(\frac{v}{ISV+u}\right)^a\left(\frac{SV_f}{X_i}\right)^b\right], \tag{9}$$

where a, b are exponents and c is proportionality constant. This type of equation is very practical for correlating experimental data. Empirical parameters of the Eq. (9) were evaluated using an Excel spreadsheet with the built-in/nonlinear optimization package. The optimum values are: $c = 0.13$, $a = 0.98$, and $b = 0.52$. The parameters a and b were rounded off to 1 and 0.5, respectively, in order to make the calculations simpler. Substitution of c, a, and b estimates into Eq. (9) resulted in the following:

$$\ln\left[\frac{X_{SB}}{X_u}\right] = 0.13\left[\left(\frac{v}{ISV+u}\right)\left(\frac{SV_f}{X_i}\right)^{(1/2)}\right]. \tag{10}$$

The usefulness of Eq. (10) for predicting the X_{SB} in the settling tank was tested by performing a regression of the predicted X_{SB} vs. the measured X_{SB} which is shown in Fig. 7. The coefficient of determination (r^2) is 0.82 which indicates that 82% of the variation in the measured X_{SB} can be described by the observed values of X_{SB}. The slope of the best fit line is not significantly different from 1 (45° line) and the value of the intercept is 2.4 mg/l which is not significantly different from zero.

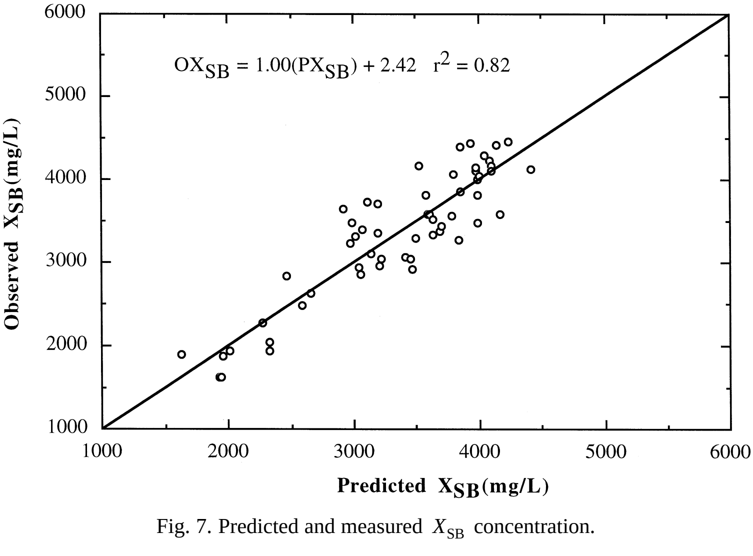

Fig. 7. Predicted and measured X_{SB} concentration.

3.4. Interpretation of the new estimation method

The new estimation equation indicates that X_{SB} is affected by the SVI and by hydraulic conditions in the settling tanks. It seems likely that the effect of SVI on X_{SB} will be similar for most activated sludge processes. However, the effect of the hydraulic conditions in the settling tanks on X_{SB} may vary for different activated sludge processes because many different settling tank designs have been used. Also, the effect of hydraulic conditions in the settling tanks should depend upon the depth of the sludge blanket.

The upper boundary of Eq. (10) can be conceptualized by considering that as the overflow rate approaches zero, $\ln[X_{SB}/X_u]$ also approaches zero which means that X_{SB} approaches X_u. When there is very small inflow $(Q+Q_r)$ to the settling tanks, the sludge blanket depth will be very low and all of the sludge will thicken to the underflow suspended solids concentration. When the overflow rate $(v=Q/A_s)$ is increased relative to a given $\mathrm{ISV}+u$, the sludge blanket would be expanded due to the upward flow of water through the settling sludge. Takacs et al. [7] explained this phenomena using the concept of particle size distribution. As the overflow rate increases, particles in the settling sludge are fluidized and carried upward. This fluidization causes the transfer of solids to the upper part of the settling tank, increases the sludge blanket depth and decreases the X_{SB}. On the other hand, either a high zone settling velocity (ISV) or an increase in the underflow rate $(u=Q_r/A_s)$ will counteract the effect of a higher v. These concepts are true in a qualitative sense but probably will vary quantitatively depending on the design of the settling tanks.

A higher $\mathrm{SV_f}/X$ was found to result in a lower S_{SB}. This should be obvious because $\mathrm{SV_f}/X$ measures the volume (l/l) occupied by 0.001 kg/kg of sludge solids after 30 min settling and the volume occupied by the sludge during settling would also be expected to be higher. This aspect of the problem was previously studied by other investigators. For example, Parker [12] concluded that in shallow settling tanks (1.2–2.27 m deep) studied by Pflanz [6], the higher sludge blanket depth was associated with higher SVI values.

3.5. Simpler estimation technique

Eq. (10) may be a bit cumbersome for many plant operators to use routinely. In an attempt to find an estimation equation which would be more readily accepted by plant operators, we tried correlation of X_{SB} with X, X_u and $\mathrm{SV_f}$. Data from two sampling trips when the settling tanks were hydraulically overloaded were eliminated from the data set used for these regressions. The resulting best fit equation is:

$$X_{SB}=0.11\left[(X+X_u)/\mathrm{SV_f}\right]-368. \tag{11}$$

A plot of X_{SB} vs. $(X+X_u)/\mathrm{SV_f}$ is presented in Fig. 8 to illustrate how well the equation represents the data.

The coefficient of determination is 0.70 which is clearly better than the 0.44 obtained for the method of averaging X and X_u. Eq. (11) could be used by an operator as easily

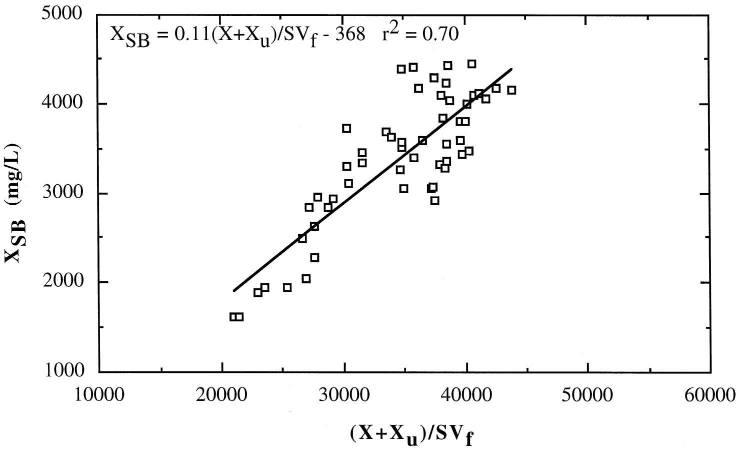

Fig. 8. Linear regression of a simplified method.

as Eq. (6) to give an improved estimate of X_{SB} for normal flow conditions. However, in order to determine the capacity of the settling tanks to store sludge during a hydraulic overload, an approach similar to that embodied in Eq. (10) should be used.

4. Summary and conclusion

The sludge in the activated sludge clarifiers can be sampled without causing any back-mixing of solids by using an simple integrated sampler. There is no significant difference between the average SBD and the SBD measured at halfway between the center and periphery of the settling tanks. Sampling at halfway between the center and periphery of the settling tank gives a good approximation of the average X_{SB} in the settling tanks.

The average X_{SB} tends to increase with an increase in either X or X_u. However, the correlation indicates that only 44% of the variation in the measured X_{SB} is related with sum of X and X_u. The method of averaging X and X_u tends to overestimate the X_{SB}.

A new empirical model for predicting X_{SB} was developed. The logarithmic ratio of X_{SB} to X_u was successfully related to the dimensionless plant operation variables, $v/(\mathrm{ISV}+u)$ and $\mathrm{SV_f}/X$. The empirical model has proven predictive capability of X_{SB} for the entire operating SBD and SVI range. This empirical model can be used to provide better information about the amount of sludge in the settling tanks for calculation either of the sludge residence time or of the amount of sludge stored in the settling tanks during a hydraulic overload.

Another estimation equation, $X_{SB} = 0.11[(X+X_u)/\mathrm{SV_f}]$ was also found to represent the data much better than the method of averaging X and X_u. This equation can easily be used by an operator for estimating X_{SB} during normal flow conditions; however, it does not apply during hydraulic overload conditions.

Appendix A. Nomenclature

A_s	Surface area of the settling tanks [ft^2 or m^2]
f	Unit conversion factor (8.34 lb/gal or 0.001 kg/g)
ISV	Initial settling velocity (zone settling velocity at X) [ft/d or m/d]
J_e	Mass flow of suspended solids in the overflow (effluent) from the settling tanks [lb/d or kg/d]
J_m	Mass flow of suspended solids in the mixed liquor flow from the aeration tanks to the settling tanks [lb/d or kg/d]
J_r	Flow of suspended solids in the return sludge from the settling tanks to the aeration tanks [lb/d or kg/d]
J_u	Flow of suspended solids in the underflow from the settling tanks [lb/d or kg/d]
J_w	Flow of suspended solids in the waste sludge [lb/d or kg/d]
M_a	Mass of suspended solids in the aeration tanks [lb or kg]
M_s	Mass of suspended solids in the settling tanks [lb or kg]
Q	Flow rate of process influent [million gallons per day or m^3/d]
Q_r	Flow rate of return sludge [million gallons per day or m^3/d]
Q_w	Flow rate of waste sludge [million gallons per day or m^3/d]
SBD	Sludge blanket depth [ft or m]
SV_f	Sludge volume after 30 min of settling expressed as a fraction [l/l]
SVI	Sludge volume index [ml/g]
t	Time [h]
Δt	Period of time for evaluation of solids accumulation in the settling tanks [h]
u	Underflow velocity (Q_r/A_s) [m/d]
v	Overflow rate (Q/A_s) [m/d]
V_a	Volume of aeration tanks [million gallons or m^3]
V_s	Volume of sludge blanket [million gallons or m^3]
X_{SB}	Average suspended solids concentration in the sludge blanket [$mg/l = g/m^3$]
X_e	Effluent (overflow) suspended solids concentration [$mg/l = g/m^3$]
X	Mixed liquor suspended solids concentration [$mg/l = g/m^3$]
X_i	Mixed liquor suspended solids concentration expressed as a dimensionless ratio [kg/kg]
X_u	Underflow liquor suspended solids concentration [$mg/l = g/m^3$]
θ_x	Mean cell residence time [days]

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