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MICROBIAL AGGREGATES IN WASTEWATER TREATMENT

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ABSTRACT

Basic forms of microbial aggregates generated in wastewater treatment and techniques used to study them, are described and discussed. The role of the free-setting velocity in evaluation of some physical properties of activated sludge flocs is emphasized. Several regression models were applied to correlate the flocs' settling velocity with flocs' size values. For the studied samples a simple linear model proved to be superior to a multiplicative one, and an introduction to this model of a settling shape factor function instead of constant intercepts, provided a very good correlation of the experimental data. It is expected that a difference between shape factors for the most stable conditions of the flocs and those for the flocs under the settling conditions will make it possible to determine softness or stiffness of these microbial aggregates.

KEYWORDS

Flocs; free-settling; microbial aggregates; shape factors; size values.

INTRODUCTION

Microbial aggregates in wastewater treatment are generated in two basic forms: as suspended flocs and as biological films. A combination of these forms also exists. Fig. 1 shows a general systematics of wastewater treatment processes associated with specific forms of microbial aggregation. Biomass in various modifications of activated sludge process (Ganczarczyk, 1983) represents suspended growth forms (biological flocs). Microbial growth on solid surfaces in the form of biological films is represented in biological filtration and in rotating biological disks processes. Biological films on solid surfaces and suspended biological growths exist jointly in such hybrid growth processes as fluidized biological beds and carrier activated sludge. Moreover, sloughing aggregates of biofilms closely resemble some kinds of activated sludge flocs.

Physical properties of different types of biological growth differ markedly, although they depend simultaneously on several other factors. In general, density of biological flocs is much lower than that of biological films, allowing for much higher concentration of biomass per unit volume in fluidized bed and activated sludge carrier processes than is possible in various other modifications of activated sludge. However, the density of individual activated sludge flocs is a function of their dispersion; small flocs are denser than larger flocs, and the flocs' size/density relationships has a form of a hyperbolic function (Li and Ganczarczyk, 1987). The density of biological films is a function of biological load to which these films are exposed and differs in time of the film maturation (Zahid and Ganczarczyk, 1993).

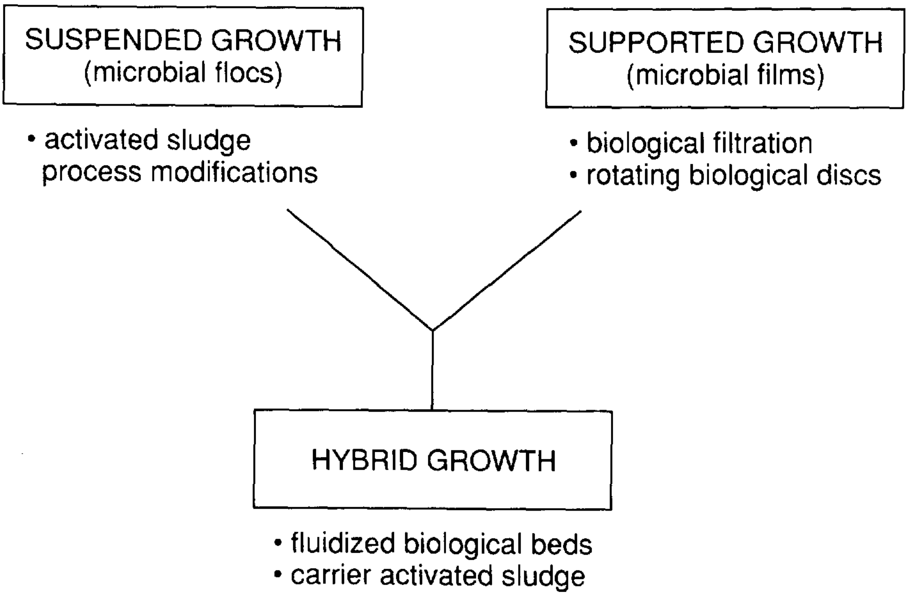

Fig. 1. General systematics of wastewater treatment processes associated with suspended and supported microbial growth.

Microbial aggregates may be considered as composite materials. They contain zooglear and filamentous bacterial cells and extracellular polymers. Physical characteristics of these components are drastically different: bacterial cells are entities protected by very strong bacterial walls, while extracellular polymers in general do not show noticeable physical integrity, although it is possible that they may differ substantially in this respect even in the scope of particular aggregates. In previous work, Li and Ganczarczyk (1990) noticed that specific types of micro-organisms were not distributed uniformly in activated sludge flocs, but formed individual micro-colonies which were composed of bacteria morphologically different from those in the neighbouring micro-colonies. This allows one to assume that microbial aggregation may be of a multi-level character, and that the specific micro-colonies should be considered as secondary types of primary particles. The multi-level aggregation is a well accepted fact in the field of water coagulation flocs (e.g. Clark and Flora, 1991).

The most often studied physical properties of activated sludge flocs include determination of their dispersion or size distribution (Ganczarczyk and Kosarewicz, 1961; Ganczarczyk, 1967; Li and Ganczarczyk, 1991 and 1992), density/porosity (Li and Ganczarczyk, 1987), permeability (Li and Ganczarczyk, 1988 and 1992), settling velocity (Li and Ganczarczyk, 1987), microtome sectioning of flocs embedded in paraffin (Li and Ganczarczyk, 1990) or resin (Ganczarczyk *et al.*, 1992), image analysis of floc embedded in agar (Li and Ganczarczyk, 1986; Ganczarczyk *et al.*, 1992), image analysis of settling tests recorded on photographic film, and image analysis of paraffin or resin embedded microtome section of flocs. Data processing in these studies covers estimation of floc size distribution (Li and Ganczarczyk, 1991), formulation settling velocity relationships, and fractal analysis of geometric properties of flocs and flocs sections (Li and Ganczarczyk, 1989 and 1990). A schematic presentation of the scope of such studies is presented in Fig. 2.

In this work, attention is directed to the relationship between free-settling velocity of the activated sludge flocs and the flocs' size values.

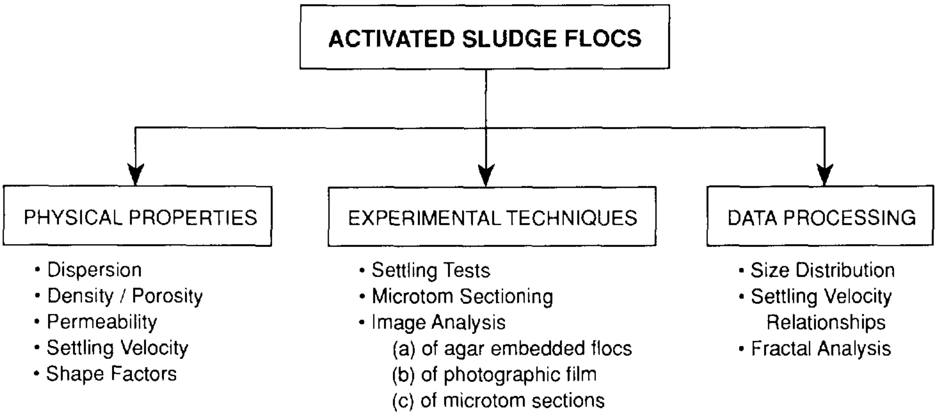

Fig. 2. Scope of the studied physical properties of activated sludge flocs, and the respective experimentation and data processing techniques.

SETTLING VELOCITY RELATIONSHIPS

Several observations indicate that a functional relationship between free-settling velocity of activated sludge flocs and characteristic dimensions of these microbial aggregates reveals some intrinsic properties of the aggregates such as their structure and patterns of aggregation. The settling rate of the particle aggregates depends, among other, on their density, porosity, permeability and settling shape factors which, in turn, are a function of aggregates' size and softness. In a previous paper, Li and Ganczarczyk (1987) demonstrated that, for a given sample of activated sludge flocs, the flocs' settling velocity correlated much better with a linear or a 0.55 power relationship of the flocs' cross-sectional diameter or longest dimensions, than with the second power relationship anticipated from Stokes' law. On this basis, Patry and Takacs (1992) assumed a linear relationship between free-settling velocity and floc sizes in the upper layers of secondary clarifiers.

In this work, four different samples of activated sludge mixed liquor from the Metropolitan Toronto Main Wastewater Treatment Plant were subjected to free settling tests following the procedure described before (Li and Ganczarczyk, 1987). The number of flocs measured in each sample ranged from 21 to 83; the total number of measurements made was close to 200. The photographic film records were processed by an image analysis system employing the Bioquant IV software (R & M Biometrics, Inc., Nashville, TN). The measured values were as follows: free-settling velocity (V), flocs' longest dimension (L), flocs' longest diameter perpendicular to the settling direction (D_p), flocs' perimeter (P), and the flocs' two-dimensional area (A) equal to the settling floc projection. The values of flocs' equivalent diameter (D) were calculated from the values of A, and those for two-dimensional settling shape factor (ξ_2) were calculated from the values of A and P, following the equation that $\xi_2 = 4\pi A/P^2$ (Allen, 1981). The statistical analysis of this information was carried out using the statistical software package Statgraphics, version 3.0 (Statistical Graphics Corp., Rockville, MD).

Table 1 presents the results of an application of a simple linear regression model ($Y = a + bX$) for the evaluation of the relationship between flocs' free-settling velocity and the flocs' longest dimension (L), longest diameter perpendicular to the settling direction (D_p), and the equivalent diameter (D). In Table 2, a multiplicative model ($Y = aX^b$) has been used for the same parameters. Eventually, in Table 3, the linear models have been appended by the information on flocs' settling shape factors (ξ_2). In the latter model, the intercept-slope linear equation was modified by introducing, instead of an intercept constant "a", a ratio of a different constant "a", divided by the respective shape factor. For all the experimental data (the samples 1–4 together), the additive, the multiplicative and modified additive models showed the results presented in Table 4.

TABLE 1. Free-Settling Velocity of Activated Sludge Flocs as Linear Functions their Size Values

For flocs' longest dimension: $V = a + bL$

SAMPLE	a	b	CORRELATION COEFFICIENT	R^2, %
1	0.0906	0.0057	0.9185	84.47
2	0.8322	0.0050	0.8418	70.86
3	0.7699	0.0050	0.9288	86.28
4	0.8660	0.0060	0.9005	81.09

For flocs' longest diameter perpendicular to the settling direction: $V = a + bD_p$

SAMPLE	a	b	CORRELATION COEFFICIENT	R^2, %
1	0.2610	0.0062	0.9038	81.68
2	1.1385	0.0050	0.8617	74.25
3	0.9270	0.0057	0.9181	84.29
4	1.1487	0.0061	0.8663	75.05

For flocs' equivalent diameter: $V = a + bD$

SAMPLE	a	b	CORRELATION COEFFICIENT	R^2, %
1	0.0762	0.0072	0.9375	87.90
2	0.4535	0.0078	0.8936	79.86
3	0.5524	0.0073	0.9363	87.67
4	0.8578	0.0077	0.8986	80.76

The application of linear regression models for evaluation of free-settling velocity of the studied activated sludge flocs as a function of their size values (Table 1) produced for the particular flocs samples high correlation coefficients and R^2 values. It confirmed the validity of such an approach. Perhaps it may be of interest to note that, in general, the linear slope factor "b" differed somewhat with the use of different size values for the flocs. It increased in the sequence from L to D_p to D. The use of multiplicative regression models for the above purpose (Table 2) showed high exponent "b" values indicating almost a linearity of the relationship (b close to 1). However, the R^2 values for these models were lower than those for the linear regressions. The application of modified linear regression models incorporating flocs' settling shape factors

(Table 3) drastically improved R^2 values of the relationships as compared with the already good R^2 values for the linear regression models presented in Table 1. The former values were in the range from 94.26 to 96.86%, and the latter in the range from 70.86 to 86.28%. It should also be noted that the introduction of this modification practically did not change the linear slope values "b" in the relationship, but affected mostly the intercept values converting them from simple constants into functions of settling shape factors. The noted improvement of R^2 values indicated an important influence of settling shape factors on free-settling velocity of activated sludge flocs. The application of linear, multiplicative, and modified linear regression models to all the experimental data (Table 4) showed again the best R^2 values for the modified linear models (from 92.72 to 94.56%), followed by those linear models (from 76.55 to 81.41%) and for multiplicative models (from 71.79 to 74.74%).

TABLE 2. Free-Settling Velocity of Activated Sludge Flocs as Multiplicative Functions of their Size Values

For flocs' longest dimension: $V = aL^b$

SAMPLE	a	b	CORRELATION COEFFICIENT	R^2, %
1	0.000082	0.8142	0.9231	85.21
2	0.000184	0.7940	0.8562	73.31
3	0.000587	0.7119	0.8659	74.98
4	0.000895	0.7071	0.8176	66.85

For flocs' longest diameter perpendicular to the settling direction: $V = aD_p^b$

SAMPLE	a	b	CORRELATION COEFFICIENT	R^2, %
1	0.000457	0.7093	0.9057	82.04
2	0.001550	0.6625	0.8637	74.59
3	0.002050	0.8368	0.8368	70.03
4	0.003194	0.6331	0.7776	60.48

For flocs' equivalent diameter: $V = aD^b$

SAMPLE	a	b	CORRELATION COEFFICIENT	R^2, %
1	0.000123	0.8189	0.9342	87.28
2	0.000104	0.8770	0.8922	79.60
3	0.000663	0.7349	0.8673	75.23
4	0.001387	0.7049	0.8193	67.13

TABLE 3. Free-Settling Velocity of Activated Sludge Flocs as Modified Linear Functions their Size Values

For flocs' longest dimension: $V = a/\xi_2 + bL$

SAMPLE	a	b	R^2, %
1	0.0210	0.0058	94.26
2	0.1295	0.0057	94.55
3	0.3362	0.0048	95.79
4	0.3909	0.0055	94.49

For flocs' longest diameter perpendicular to the settling direction: $V = a/\xi_2 + bD_p$

SAMPLE	a	b	R^2, %
1	0.1416	0.0061	93.23
2	0.2486	0.0052	93.85
3	0.4147	0.0053	95.52
4	0.5253	0.0054	93.04

For flocs' equivalent diameter: $V = a/\xi_2 + D$

SAMPLE	a	b	R^2, %
1	0.0364	0.0073	95.59
2	0.1399	0.0078	96.86
3	0.2838	0.0069	96.71
4	0.3867	0.0071	94.38

The size values studied of the activated sludge flocs, longest dimension (L), longest diameter perpendicular to the settling direction (D_p), and equivalent diameter (D), had different influence, on the regression models considered. As shown in Tables 1–4, the highest R^2 values were calculated for regressions based on equivalent diameter, followed by those based on longest dimension, and those based on longest diameter perpendicular to the settling direction. The latter finding was somewhat surprising, as from a conventional approach to the free-settling mechanism, it might be expected that these measurement could be more meaningful than the other used in this study.

TABLE 4. Free-Settling Velocity of Activated Sludge Flocs as Line Ar, Multiplicative and Modified Linear Function of Flocs for all the Experimental Data Size Values

MODEL	a	b	CORRELATION COEFFICIENT	R^2, %
$V = a + bL$	0.4656	0.0057	0.8900	79.22
$V = a + bD_p$	0.6791	0.0061	0.8749	76.55
$V = a + bD$	0.3654	0.0078	0.9023	81.41
$V = aL^b$	0.00014	0.8115	0.8593	73.85
$V = aD_p^b$	0.00062	0.7234	0.8437	71.79
$V = aD^b$	0.00018	0.8260	0.8644	74.74
$V = a/\xi_2 + bL$	0.2598	0.0052	-	93.52
$V = a/\xi_2 + bD_p$	0.3588	0.0055	-	92.72
$V = a/\xi_2 + bD$	0.2427	0.0071	-	94.56

SHAPE FACTORS OF ACTIVATED SLUDGE FLOCS

Two dimensional shape factors for activated sludge flocs can be considered under free-settling conditions (settling shape factors) or under most stable conditions for the flocs, e.g. for flocs embedded in solidified agar (Ganczarczyk *et al.*, 1992). In the former case, the floc shapes are affected by gravity and drag forces, while in the latter case, the flocs are isolated from any external influences. It may be hypothesized that any difference between settling shape factors and such factors measured for the most stable conditions for the flocs would characterize the softness or stiffness of the aggregates. Under practical conditions, however, measurements of factors leading to calculation of both types of shape factors refer usually to different size ranges of the flocs, which only partially overlap. It is due to the limitations of the applied settling tests technique (Li and Ganczarczyk, 1987). In Fig. 3 and 4, there are presented examples of floc size functions for two series of measurements of both types of shape factors. The shape factors for smaller flocs are larger as their forms more closely approximate a projection of a sphere for which the shape factor would be equal to one. With the increase in floc size, the shape factors decrease because the shape of these flocs tend to differ more from a sphere. Moreover, the shape factors for the most stable conditions are always larger for the flocs of the same size than the settling shape factors. The values of settling shape factors used in Tables 3 and 4 can be generalized by the formula:

$\xi_2 = 1.730\ (1/L)^{0.23}$ with $R^2 = 95.22\%$.

CONCLUSIONS

1. Biological treatment of wastewater is based on suspended or supported microbial growth. Microbial aggregates may be considered as composite materials and microbial aggregation may be a multi-level phenomenon. Several physical properties of activated sludge flocs are considered and several experimentation and data processing techniques are used for this purpose.

2. Application of linear regression models for evaluation of free-settling velocity of activated sludge flocs in the samples of mixed liquors studied showed high correlation coefficients and R^2 values. These models proved to be superior to the respective multiplicative regression models.

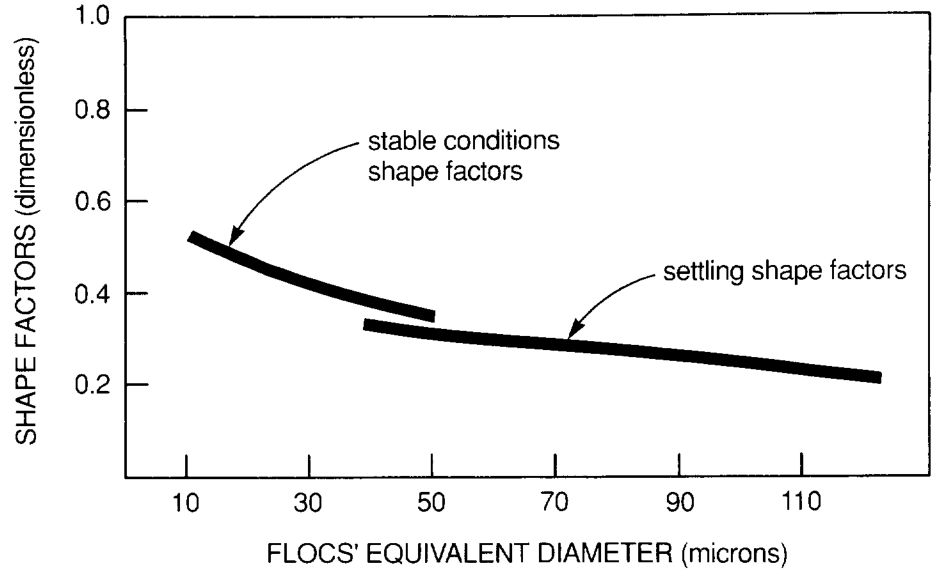

Fig. 3. Shape factors of activated sludge flocs (Experiment A).

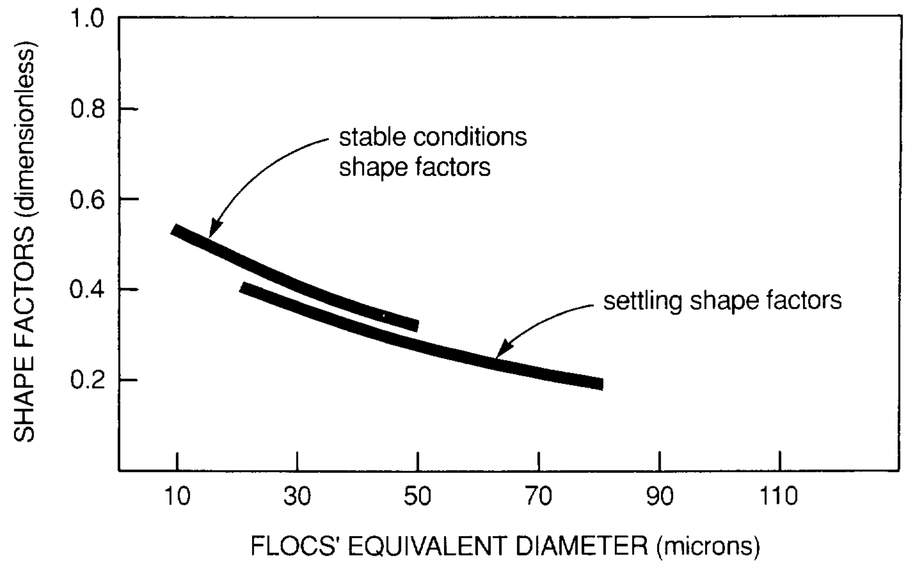

Fig. 4. Shape factors of activated sludge flocs (Experiment B).

3. A modification of the above linear regression models, by an introduction of functions of settling shape factors instead of constant intercepts, drastically improved the already good R^2 values of the relationships. It indicated an important influence of settling shape factors on free-settling velocity of activated sludge flocs.

4. Similar results were derived from an application of the above regression models to all the experimental data covered by this work.

5. Among size values of the activated sludge flocs, the measurements of equivalent diameter led to the highest R^2 values in the regression models for evaluation of flocs' free-settling velocity.

6. Shape factors of activated sludge flocs can be differentiated into those under settling conditions, and those under most stable conditions. A difference between these two types of shape factor may be used as a measure of softness or stiffness of the flocs.

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