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RAPID DETERMINATION OF FRACTAL STRUCTURE OF BACTERIAL ASSEMBLAGES IN WASTEWATER TREATMENT: IMPLICATIONS TO PROCESS OPTIMISATION

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ABSTRACT

A rapid method of determining the structure of aggregated particles using small angle laser light scattering is applied here to assemblages of bacteria from wastewater treatment systems. The structure information so obtained is suggestive of fractal behaviour as found by other methods. Strong dependencies are shown to exist between the fractal structure of the bacterial aggregates and the behaviour of the biosolids in zone settling and dewatering by both pressure filtration and centrifugation methods. More rapid settling and significantly higher solids contents are achievable for "looser" flocs characterised by lower fractal dimensions. The rapidity of determination of stuctural information and the strong dependencies of the effectiveness of a number of wastewater treatment processes on aggregate structure suggests that this method may be particularly useful as an on-line control tool. © 1998 Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Fractal dimension; wastewater; floc structure; small angle light scattering; dewatering; settling.

INTRODUCTION

The structure of bacterial aggregates is recognised to be a critical determinant of the rate of many wastewater treatment processes including sedimentation, flotation and dewatering. Despite the apparent importance of aggregate structure in these processes, difficulties in quickly obtaining some measure of "structure" have limited the use of such a parameter in optimising treatment steps. Techniques such as settling velocity measurement (Namer and Ganczarczyk, 1993; Lee *et al.*, 1996) and microscopic analysis (Ganczarczyk *et al.*, 1992) do provide insight into the structure of aggregated materials but are extremely tedious to implement and totally unsuited to any form of rapid, "on-line" analysis of the type that would be required to implement feed-back modification of aggregate structure with a view to optimising the operational efficiency of a given unit process.

While the aforementioned techniques are ill-suited to rapid determination of "structure" parameters, they have been of use in demonstrating the "fractal" nature of bacterial aggregates typical of wastewater treatment systems (Li and Ganczarczyk, 1990; Ganczarczyk, 1994; Johnson *et al.*, 1995). The fractal description of aggregate structure was developed by Mandelbrot (1983) and may be best summarised by recognising that for solid objects, the mass M of the object is proportional to its size R raised to some integer value, D. That is:

$$M(R) \alpha R^D$$

where D = 1, 2 and 3 for linear, planar and three dimensionally compact objects respectively. For a porous aggregate, the exponent D may take a fractional value, the so-called "fractal dimension". Thus, "compact" aggregates have been found to have fractal dimensions in the 2.3 to 2.5 range (or higher if "restructuring" occurs) while "loose" aggregates typically have fractal dimensions in the 1.7-1.8 range (Logan and WiLkinson, 1990; Amal *et al.*, 1990).

X-ray, neutron and light scattering techniques have been widely used to determine the fractal dimensions of colloidal aggregates (Auvray, 1990) but have not been suitable for the determination of structure information for larger particles such as bacterial assemblages typical of wastewater treatment systems. Recently, however, Jung *et al.* (1995) have reported the successful determination of fractal dimensions for hematite aggregates of a few microns in diameter using light scattering at small angles of deviation from the incident beam. This technique holds promise for the rapid determination of structure information for wastewater aggregates.

In this paper, we report on the use of the so-called Small-Angle Laser Light Scattering (SALLS) technique for determining information on the structure of bacterial assemblages from an activated sludge plant. In addition, we overview the relationship between structure factors determined by SALLS and operational characteristics of selected wastewater treatment processes. In particular, attention is focussed on the impact of aggregate structure on the thickening and dewatering of biosolids.

EXPERIMENTAL METHODS

Fractal dimension measurement by small angle laser light scattering

Scattering experiments give access to the position correlations between particles in an aggregate and consequently are a very useful tool to measure the fractal dimension of aggregates (Jullien and Botet, 1987). In a scattering experiment, a beam of light of intensity I_0 is directed onto a sample and the scattered intensity (in photon counts) is measured as a function of angle θ to the incident direction. The incident and scattered beams are characterised by the momentum transfer **Q**, with

$$Q = |\mathbf{Q}| = 4\pi n \sin(\theta/2)/\lambda_0,$$

where λ_0 is the wavelength and n is the refractive index of the medium.

At small scattering angles, it can be shown that:

$$I(Q) \propto Q^{-dF}$$

provided $Qa \ll 1 \ll Qd$ where a is the diameter of the constituent particles of the floc and d is the diameter of an equivalent sphere that describes the floc. For flocs exhibiting such "power-law scattering", a plot of log I versus log Q should yield a straight line of slope equal to the fractal dimension, d_F.

Small-Angle Laser Light Scattering was used in this study to measure the structure and the size of the flocs. The instrument available for the small angle light scattering experiment was the Malvern Mastersizer/E which consists of a 5mW He-Ne laser (λ of 632.8 nm) as the light source, an optic lens, and a series of photo sensitive detectors. The particles pass through the expanded and collimated laser beam in front of the optic lens in whose focal plane are positioned 31 photo sensitive detectors. The Fourier optics can be used with 45mm, 100mm, or 300mm lenses which allow the collection of light scattered at angles from 0.01° to 32.5°. In this work, the flocs were analysed using the 300mm lens enabling the collection of light scattered from 0.03° to 6.25°. Samples of biosolids were taken from specific locations within selected wastewater treatment plants in Sydney and diluted to obtain an obscuration level between 10 to 30~o before the flocs structure and size were analysed by the small angle light scattering technique. A complete analysis of the applicability of this technique to determination of biosolids structure is given elsewhere (Guan *et al.*, in press).

Thickening and dewatering of biosolids

Preconditioning. Waste activated sludge samples were obtained from either St Mary's or Quaker's Hill sewage treatment plants in Sydney. Cationic polymers are routinely used to improve settleability and dewatering of sludges from these plants (Zetag 53 at Quaker's Hill and Zetag 92 at St Mary's) and the same polymers were used to modify the characteristics of the sludges in the settling and dewatering tests described below.

Sludge thickening. Zone settling tests were undertaken in the laboratory in a transparent 1.5 litre cylinder filled with sludge and mixed to distribute the solids evenly. Sludges were obtained from the chosen wastewater treatment plant and a predetermined amount of polymer added. The sludge was then placed in the settling column and the height of the solid-liquid interface was recorded over time. The same procedure was followed for a range of polymer doses. The structure of the conditioned sludges was measured using the light scattering method described above.

Pressure filtration dewatering. Pressure filter dewatering studies were carried out in a laboratory scale cylindrical cell measuring approximately 6 cm in diameter and 15 cm in height fitted with a pneumatically operated piston with which to apply pressure. Porous sintered steel plates of 10 µm nominal pore size were fitted over the base plate and over the end of the plunger. Both the base and plunger were attached to a vacuum line to facilitate removal of filtrate from the cell. A pressure of 400 kPa was applied to the piston from a pneumatically operated piston and the mass of water removed measured as a function of time. Polymer for sludge conditioning was mixed with the sludge before dewatering. At the end of each experiment, the cake was weighed and its solids content measured gravimetrically by drying in an oven at 110°C for 16 hours. The same procedure was followed for a range of polymer doses.

The pressure filtration cell was equipped for electrically-enhanced dewatering (EDW) through application of electrical current through the cell. A number of studies were thus carried out to assess the impact of biosolids structure on the cake solids content achievable by EDW. A current loading of 71 A/m^2 was applied in the EDW process.

Centrifugal dewatering. Studies of the impact of biosolids structure on centrifugal dewatering has been investigated in the laboratory and at full scale. In the laboratory, the solids contents achieved for sludges conditioned with various doses of polymer were determined after centrifuging in a Spintron GT-175S bench top instrument at 3,000 rpm.

Investigations into the impact of biosolids structure, following conditioning with polymer, on solids content achieved have also been undertaken at full scale using a Humbolt decanter centrifuge at Quaker's Hill. This centrifuge has a bowl diameter of 520 mm and operates at a speed of up to 2,200 rpm. In these studies, polymer dose was varied and the solids content achieved determined. Given the difficulty of sampling the conditioned sludge influent (the polymer is dosed within the centrifuge), the structure of solids remaining in the centrate was measured usin~ the Malvern Mastersizer and the SALLS method described above.

RESULTS AND DISCUSSION

Structural properties of preconditioned sludge

Results obtained from the slope of log I versus log Q plots for biosolids from the St Mary's plant preconditioned with various doses of cationic polymer (Zetag 93) are shown in Table 1. We will refer to the slope of log I vs. log Q plots as a "fractal dimension" throughout this paper though it should be noted that the size range over which self-similar behaviour is observed is relatively limited. The possibility of deviation in slope from that expected of a system of "pure" fractal scatterers should also be kept in mind. As noted by Bushell *et al.* (1996), heterogeneity in the sizes of constituent particles may introduce deviation from the slope expected if the primary particles were of uniform size. In the case of activated sludge flocs as examined here, we would not expect heterogeneity factors to compromise significantly the results since the primary particles (the bacteria) in an activated sludge would be expected to exhibit a relatively narrow size range.

The fractal dimension results obtained from small angle light scattering have been compared elsewhere (Guan *et al.*, 1997) with those obtained from aggregate settling experiments. While determination of structure information from settling rate measurements is problematic given the variety of possible drag coefficient formulations (and is certainly exceedingly time consuming), the equivalence achieved between the two approaches in these studies (for a reasonable choice of drag coefficient) is satisfying. This correspondence between two quite independent techniques adds weight to the claim that the SALLS technique may become an invaluable "on-line" tool for structure analysis and subsequent process optimisation.

The results presented in Table 1 indicate that addition of cationic polymer results in a significant lowering of the fractal dimension of the system of aggregated flocs. That is, increasing polymer addition results in an increase in porosity of the aggregates. This presumably occurs as a result, in part, of the (stronger) linkages created between individual particles by the "sticky" polymer.

Table 1. Impact of increasing polymer dose on fractal dimension of St Marys biosolids and resultant cake solids contents achieved by pressure filtration in the absence and presence of electrical enhancement

Polymer Dose (%)	Fractal dimension	Cake solid content (without electricity) (%)	Cake solid content (with electricity) (%)
0.0	2.23±0.01	2.94±0.68	3.24±0.56
0.1	1.99±0.02	5.45±1.02	16.26±1.24
0.2	1.90±0.01	16.43±1.56	24.45±2.65
0.3	1.83±0.03	19.28±2.35	36.64±2.85
0.4	1.78±0.01	21.88±1.54	39.06±2.04
0.6	1.78±0.02	22.24±2.12	41.85±2.65

Effect of structure on dewatering by pressure filtration

The solids contents achieved on biosolids dewatering by pressure filtration in the absence and presence of electrical enhancement are given in Table 1 and shown in Figure 1. Much higher solids contents are achieved for aggregates possessing lower fractal dimensions, i.e. for solids that are less compact. Presumably, looser suspended aggregates result in formation of a more porous cake which, in turn, enables achievement of a drier product. This is particularly the case for solids dewatered by pressure filtration with electrical enhancement. Thus, for "loose" flocs of low fractal dimension, a solids content of over 40% can be achieved within 30 minutes at an applied pressure of 40 kPa and current density of 71 A/m^2. Further details of this work are reported by Guan *et al.* (in preparation).

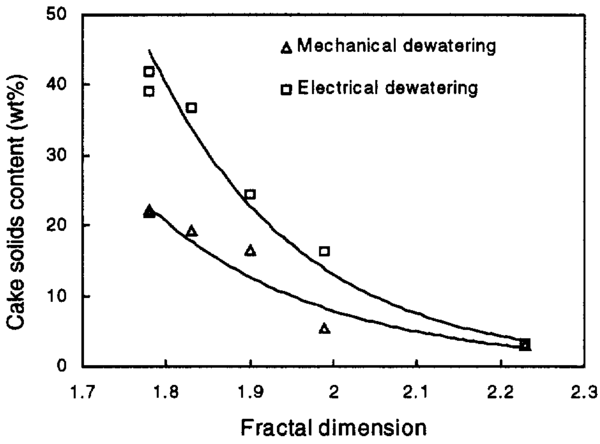

Figure 1. Solids content achieved on pressure filter dewatering of St Mary's waste activated sludge in the absence and presence of electrical enhancement.

Effect of structure on dewatering by centrifugation

The size and structure of biosolids aggregates would also be expected to affect dewatering by centrifugal methods. The correspondence between suspended biosolids structure and laboratory scale centrifugability is shown in Figure 2.

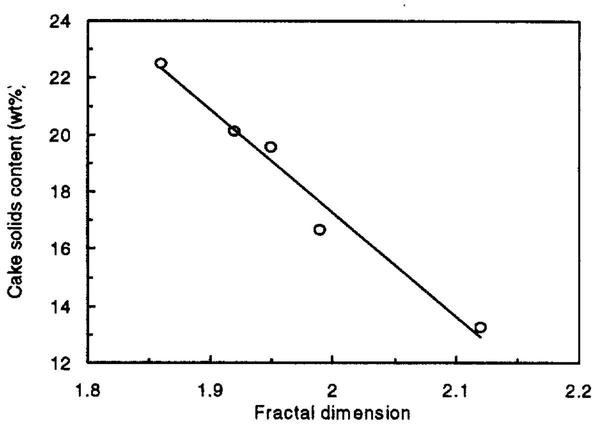

Figure 2. Solids content of biosolids of varying fractal dimension after dewatering in a laboratory centrifuge at 3000 rpm.

The apparent linear relationship between cake solids achieved and biosolids fractal dimension is a little surprising since the size of aggregates increases with increasing polymer dose and might be expected to have an impact on centrifugability. Supplementary results however (Guan, 1998) suggest that particle size has a minor impact on solids content that can be achieved under these test conditions. These results suggest that rapid, on-line determination of aggregate fractal dimension could be a useful parameter in controlling polymer dose to biosolids undergoing centrifugal dewatering.

Full scale testing of the possibility of using fractal dimension to control centrifugal dewatering has been conducted at the Quaker's Hill wastewater treatment plant in Sydney (Guan, 1998). In the centrifuge the sludge solids are thickened into a cake and the released water is discharged as the centrate. Polymer is added to the sludge within the centrifuge just before the sludge is accelerated to the speed of the spinning bowl. Good results are represented by a dry cake and a clean centrate. The test results shown in Figure 3 were obtained by varying the polymer dose to the feed sludge and sampling the resulting cake solids and centrate solids and measuring the fractal dimension of the solids remaining in the centrate.

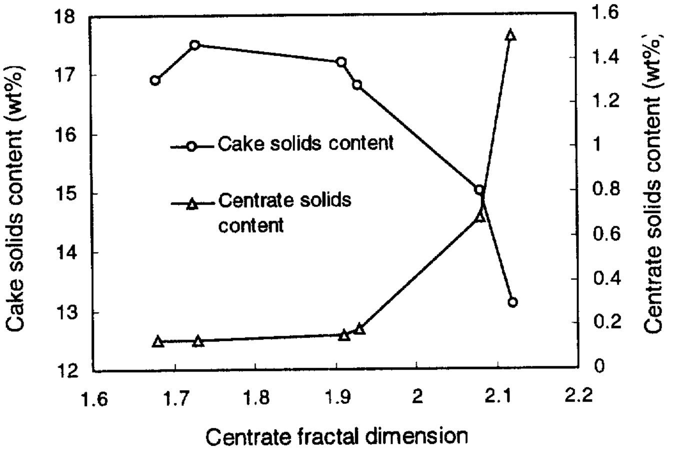

Figure 3. Total solids contents of cake and centrate obtained after centrifuging waste activated sludge from Quaker's Hill plant in Sydney. The fractal dimension (dF) of the solids (in the feed and resulting centrate) was determined by addition of various concentrations of polymer.

The centrifuge was normally operated at the polymer dose that gave a centrate fractal dimension of around 1.68. By operating at a fractal dimension of 1.92 the same level of performance can be achieved at a polymer saving of about 40%. Note that while monitoring of feed solids dF might seem a more direct measure of impact of polymer dosing, it is much simpler to obtain centrate samples from the process. In addition, the solids concentration in the centrate is usually more dilute than in the feed thus a troublesome dilution step can be avoided.

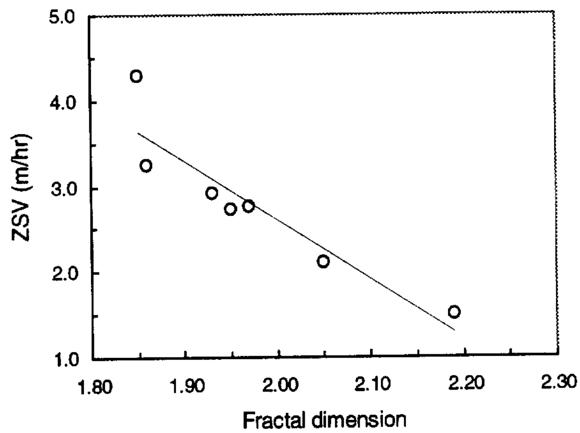

Figure 4. Zone settling velocity (ZSV) versus fractal dimension for waste activated sludge from St Mary's sewage treatment plant in Sydney

Sludge thickening

The results of the zone settling studies are shown in Figure 4. An essentially linear dependence of settling velocity on fractal dimension of polymer-conditioned flocs is observed with the less compact aggregates (lowest fractal dimension) settling most quickly. Presumably, the looser bacterial aggregates are less buoyant or more permeable, i.e. allow greater flux of water through them, and therefore settle more quickly.

CONCLUSION

From the results presented, it can be concluded that small angle light scattering provides a useful method for the rapid determination of floc structure. The method appears particularly well suited to analysis of the structure of bacterial flocs presumably due, in part, to the low refractive index of these particles. A detailed analysis of the applicability of this technique to mixed bacterial assemblages is presented elsewhere.

The solids contents achieved in pressure filtration dewatering of bacterial assemblages is strongly dependent upon the structure of the flocs - a result suggestive of maintenance of similar structural properties in the cake formed upon the filter cloth. A significant increase in solids content achieved is observed on decrease in compactness of the floc (as indicated by lower fractal dimensions).

Somewhat surprisingly, the solids content achieved in laboratory scale biosolids centrifugal dewatering trials is also strongly (linearly) dependent upon the extent of compactness of the bacterial aggregates with looser flocs dewatering to a greater extent (i.e. a higher solids content achieved). Full scale trials of the usefulness of fractal dimension as a monitor of the effectiveness of dewatering indicates that this parameter is a useful means of optimising polymer dose in dewatering.

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