On-line Particle Size Measurements in Secondary Clarifiers

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Abstract
Secondary clarification is a crucial unit process in wastewater treatment; the particulate biocatalysts are separated from the clean water by gravitation. Their gravitational settling is highly dependent on the particles' properties such as size, density and permeability. Hence, floc aggregation and disaggregation are essential to consider in the evaluation of the clarifier efficiency. The focused beam reflectance method (FBRM) is one of the rare techniques able to measure *in situ* the particle size distribution. This paper introduces the technique and demonstrates its capabilities in clarifier evaluation; benefits and drawbacks are mentioned too. In order to observe significant changes in size distribution, measurements have been performed around the flocculator under both constant and dynamic inlet flow conditions. This research has to be seen as a first exploration of this promising technique.

Keywords
FBRM, particle size, clarifier

INTRODUCTION

In wastewater engineering clean water is obtained from biodegradation of the soluble substances by microorganisms. As a result the waste is transformed in solid matter. In order to get clear water the solids are removed by gravity in the clarifier. Past research mostly concentrated on the biology and the corresponding aeration tank. Yet, the clarifier is crucial for the overall performance; improper operation results in a washout of solids and deterioration of the receiving waters would be the result.

The clarification process is driven by gravitational forces that act on the biomass particles originating from the preceding aeration tank. As long as the sludge concentration is high enough hindered-settling behavior prevails; bulk density and particle morphology are more important for process efficiency than particle size. However, above the sludge blanket the concentration is low and the regime of discrete settling is present. No hydrodynamic interaction between (discrete) particles exists and their settling is largely determined by floc properties such as density, size, permeability, etc… Of course, floc aggregation and disaggregation occur in the clarifier. This is due to both the floc properties and the hydrodynamics of the system. Indeed, shear might tear flocs apart but also might bring particles together in order to aggregate (Parker, 1970). For that reason a flocculator is built at the inlet of the clarifier; the hydrodynamic conditions are such that aggregation is enhanced.

It is obvious that the particle size distribution (PSD) is a key variable for the separation performance of the clarifier, and this is the focus of this paper. Information about the PSD can also be used to calibrate and validate so-called population balance models (Nopens *et al.*, 2002). These models describe the change of PSD, and can be applied for system optimization and evaluation with different process conditions.

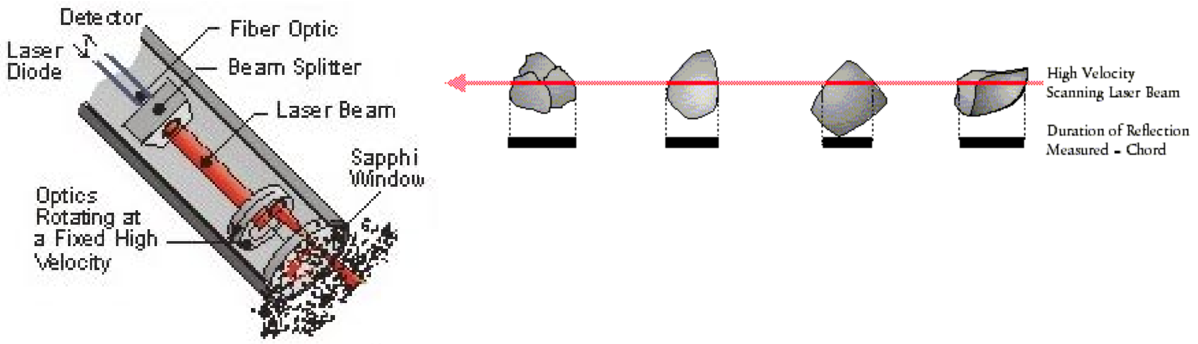
To investigate the PSD of the sludge, several sizing techniques are available. In literature, methods as image analysis (Spicer and Pratsinis, 1996), coulter counter (Li and Ganczarczyk, 1991) and laser diffraction (Biggs, 2000) are widely applied. Unfortunately, in general, they can only be applied in a lab environment and not *in situ*; mostly the device is not waterproof and fully automatic. It should be mentioned that an ocean application exists for a waterproof-made laser light diffraction system (Bale and Morris, 1987), though the practicability is questionable due to its large dimensions. Indeed, the hydraulic pattern inside the clarifier would be altered significantly. The technique also requires low sludge concentrations. Hence, on-line dilution is needed when dealing with high concentrations (Govoreanu *et al.*, 2001). As a consequence, *in situ* particle sizing techniques are rather rare. Firstly, spectroscopy of an acoustic wave reflected on the particles can reveal information on the PSD (Reichel and Nachtnebel, 1994). However, this technique is still in its infancy. Secondly, the focused beam reflectance method (FBRM) can be applied. The technique was already applied in the field of crystallization, but to the knowledge of the authors, no applications exist in wastewater treatment.

This paper starts with a presentation of the FBRM measurement principle. To show its applicability, steady-state and dynamic PSD profiling were carried out inside and outside the flocculator of a secondary clarifier. This profiling aims at demonstrating the function of the flocculator.

METHODS

The FBRM probe used in this research was the Lasentec FBRM M500 (Lasentec, Redmond, Washington, USA). It consists of a laser that is focused in some focal plane near the sapphire window (Figure 1a). The laser rotates at a fixed speed, i.e. 2 m/s, hence particle motion is insignificant to the measurement. As particles pass by the focal plane, the focused beam intersects the edge of a particle and begins to backscatter the laser light. The backscatter continues until the focused beam reaches the particle's opposite edge. The backscatter is collected by the FBRM optics and is converted into an electronic signal.

FBRM uses a discrimination circuit to isolate the time period of backscatter from one edge of an individual particle to its opposite edge. This time period is multiplied by the scan speed and the result is a distance, i.e. the *chord length* (Figure 1b). The particle size distribution measured by the FBRM is referred to as the chord length distribution (CLD). In this research, flocs were sized in the 1 to 1000 µm range over 90 logarithmic channels.



(a) (b)

Figure 1 Principle of FBRM (a) probe layout, (b) definition of chord length (from Lasentec)

As mentioned, the raw data consists of number frequencies. To calculate the respective volume frequencies the assumption is made of spherical particles.

Two issues are crucial to consider for a proper operation of the FBRM. Firstly, an appropriate flow field around the probe window has to prevail in order to measure statistically significant CLDs. Further, it has to avoid potential sticking of particles to the window as this would disturb the CLD. Fortunately, these discrepancies in CLD result in peaks that are easily filtered out. Secondly, the position of the focal point is important. Several researchers (Barrett and Glennon, 1999; Dowding *et al.*, 2001) retain the standard setting for the probe, i.e. 20 μm inside the sapphire window. According to the manufacturer, this generally results in a maximal signal-to-noise ratio. On the other hand, others focus the beam on the window itself (Williams *et al.*, 1992; Peng and Williams, 1993). Nevertheless, for specific applications it appears essential to optimize the focal point position in order to have a maximum detection of counts per second (Law *et al.*, 1997; Monnier *et al.*, 1996; Phillips and Walling, 1995a,b; Richmond *et al.*, 1998). Worlitschek and Mazzotti (2001) demonstrated that the best focal point position to detect both large and small particles is at the probe window. Further away from the window results in a stronger attenuation of the backscatter signal. Hence, small particles are not detected anymore and the big particles' size is underestimated. In this research, sludge originating from return-activated sludge, effluent and sludge from the aeration tank has been investigated for different focal point positions (data not shown). Similar conclusions as Worlitschek and Mazzotti (2001) could be drawn but two focal points were retained, i.e. one for measurements above the sludge blanket (55 μm), and one for below the blanket (280 μm).

The municipal wastewater treatment plant under study is located in Brisbane (Australia). The examined circular clarifier had a central feed, a peripheral overflow weir, a central conical sludge hopper and blade scraper. It had a maximum depth of 5.4 m and a surface area of 308 m^2. The inlet flow rate was characterized by a diurnal pattern and, during the measurement campaign, the inlet solids concentration ranged between 1800 and 2200 mg/l. It was concluded that the clarifier was underloaded in terms of solids. Hydraulically, the system was within its design boundaries. Finally, it should be mentioned that the zeolite ZELflocc was dosed in order to improve the settleability of the solids. The zeolite (approximate median diameter of 20 microns) is incorporated into the bioflocs, thus increasing the density and settling velocity of the flocs. It does not affect the operation of the clarifier.

RESULTS AND DISCUSSION

As mentioned before, CLD measurements were conducted under constant and dynamic inlet flow conditions. Below, both issues will be dealt with.

In situ steady-state CLD profiling

Measurements were taken to obtain a profile of the particle size distribution in the studied clarifier. Different locations around the flocculator were sampled. Measurements were performed at afternoon inlet flow rates (0.147 ± 0.012 m^3/s), which were the most stable that could be obtained. Sludge blanket depth measurements confirmed that the blanket was stable in the afternoon (data not shown). Inside the flocculator five CLDs were recorded at increasing depths. Measurements outside the well and at different depths were performed as well. The necessary measurement duration was determined by the total number of chord counts in order to obtain a representative CLD. Hence, all locations were sampled over a 10-minute interval, except for the four upper locations outside the flocculator. There, 30 minutes of sampling and a different focal point position were applied. The measurement periods were checked on their applicability in preliminary experiments; the total number of counts satisfactorily ranged between 400000 and 4000000.

Figure 2 shows the CLD measurements inside and outside the flocculator. At high sludge concentration all CLDs were very similar, hence they are grouped and represented by a single representative CLD in Figure 2. It is clear that the number distribution shows a slight tri-modal shape. Instead, the corresponding volume distribution looks Gaussian. Due to this apparent invariable CLD inside the flocculator, its role needs to be questioned. Presumably, most of the flocs are already formed inside the distribution pit, pipe, momentum diffuser and in the flocculator section close to the diffuser. According to Wahlberg (1992), flocculation occurs very quickly, which is in accordance with the present observations.

With the FBRM the raw data consist of the number distribution. From this the volume distribution was calculated. As long as no particles stick on the sapphire window smooth number distributions are obtained. However, accidental measurements of large particle chords may lead to peaks in the volume distribution due to their corresponding large volume. For this reason, the volume distributions look more spiky than the number distributions. Even after filtering the number distributions peaks arise with considerable gradients in frequency. If located in the higher chord length range, they might enforce the spiky behavior of some volume distributions in Figure 2. Compared to the distributions at high concentration it is clear that at low concentration both the number and volume distributions are shifted to the lower chord length range. For the most upper measurement location and next to the well this feature is most obvious. A strong peak at small chord lengths exists; this indicates that large flocs are separated by gravity. Due to the low local shear/velocity large particles are able to settle. Instead, small ones remain more in suspension due to Brownian motion.

***In situ* dynamic CLD profiling**

In this research the effect of varying inlet flow rates on the CLD has also been investigated. The measurement location was situated just outside the flocculator well and approximately 20 cm above the sludge blanket. It was assumed that shear dominated in this region and that a possible blanket rise could be observed in the CLD measurements. Figure 3 shows the temporal evolution of the CLDs with the varying flow rate. Every measurement covers 30 minutes of sampling with the FBRM probe. Again, the raw data are the number distributions and deduced from them the volume distributions. In general, similar remarks as with steady-state profiling can be made. It can be noted that at 4:30am a large particle resided in front of the window; this is no artefact but a true measurement. The CLDs shown in Figure 3 required filtering to eliminate peak counts with sharp gradients; particles sticking to the window occurred because of low flow velocities. It also seems that the rotation of the bridge was not enough to generate sufficient flow around the probe in order to remove particles from the window. However, this adverse phenomenon can be limited by choosing the proper probe position relative to the flow direction. Actually, the vertical position of the probe in this measurement campaign should be abandoned and a horizontal position preferred. Hence, particles settle perpendicular to the laser beam. More particles are scanned and the chance of sticking to the window is reduced. Regardless these comments, a shift in chord length with flow rate can be observed for the volume distribution. When the inlet flow rate increases in the morning the mean of the volume distribution increases too. This is less obvious for the number distribution.

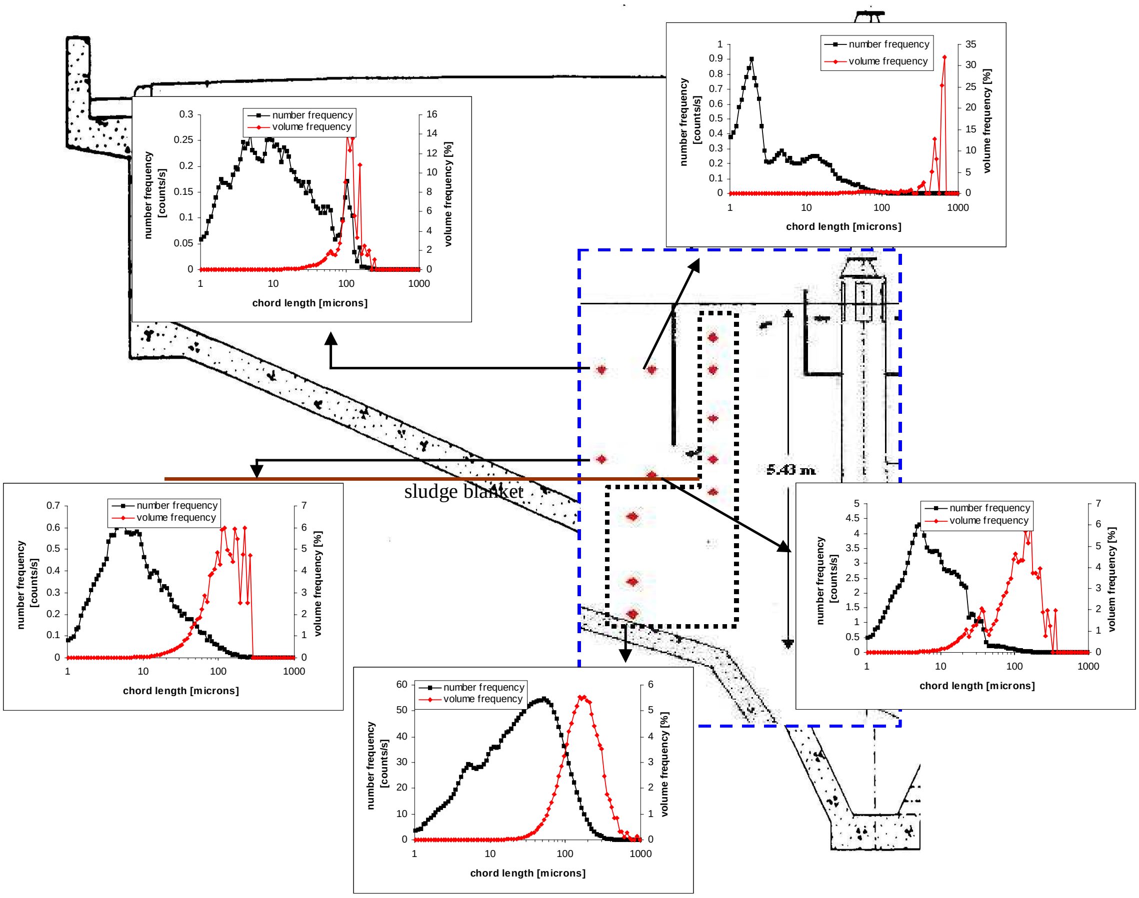


Figure 2 CLD profiling with constant inlet flow rates

It is also seen that the number frequency is related to the magnitude of the inlet flow rate. When the flow rate increases, more particles are scanned and the higher are the number frequencies. Due to the higher prevailing flow velocities, more particles are washed out of the sludge blanket or are scoured from the blanket interface.

CONCLUSIONS

To the knowledge of the authors, this research is a first attempt to measure *in situ* the particle sizes in a secondary clarifier of a wastewater treatment plant. Apparently, a steady-state for aggregation/disaggregation occurred in most of the clarifier. Since no change in CLD was observed inside the flocculator, its function with respect to flocculation was questioned. Comparison of CLDs above and below the sludge blanket clearly demonstrated the removal of the large-sized particle fractions by sedimentation.

This research also focused on some practical issues to consider. Firstly, optimization of the focal point is crucial in order to perform statistically representative measurements in the quickest way. Different focal points resulted in other CLDs. Secondly, particle velocities should be sufficiently high to avoid multiple scanning of the same particle residing in front of the probe window. In this respect the position of the probe window relative to the flow direction is essential.

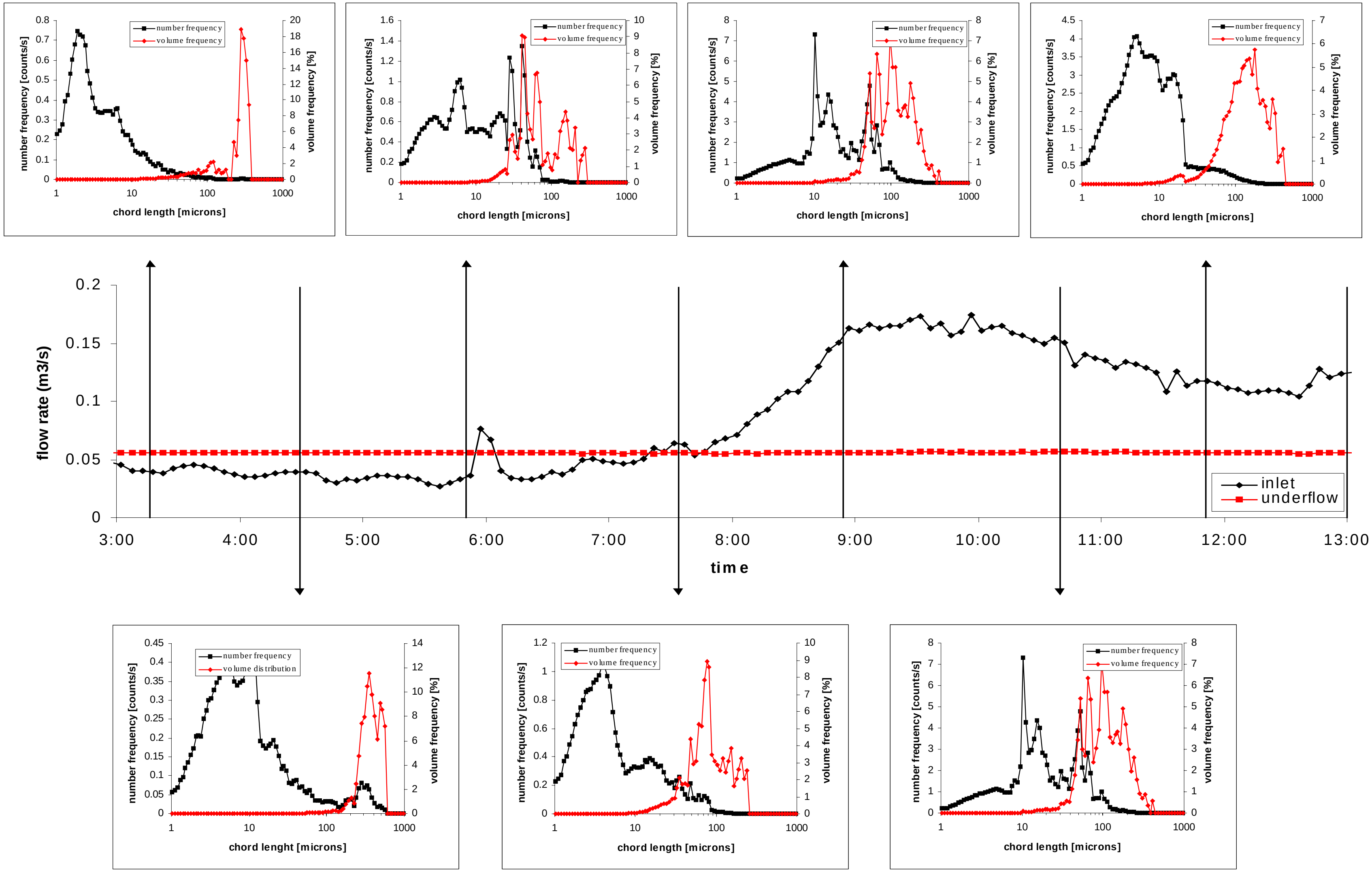


Figure 3 CLD profiling with dynamic inlet flow rates

The FBRM has proved its *in situ* applicability and the CLD can be measured in a wide range of solids concentrations. The latter is the major drawback of most alternative particle sizers.

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REFERENCES

Bale A.J. and Morris A.W. (1987). In situ measurement of particle size in estuarine waters. *Estuarine, Coastal and Shelf Science,* **24**, 253-263.

Barrett P. and Glennon B. (1999). In-line FBRM monitoring of particle size in dilute agitated suspensions. *Part. Part. Syst. Charact.,* **16**, 207-211.

Biggs C.A. (2000). *Activated sludge flocculation: Investigating the effect of shear rate and cation concentration on flocculation dynamics*. Ph.D. thesis, University of Queensland, St. Lucia, Australia.

Dowding P.J., Goodwin J.W. and Vincent B. (2001). Factors governing emulsion droplet and solid particle size measurements performed using the focused beam reflectance technique. *Colloids and Surfaces A: Physicochem. Eng. Aspects,* **192**, 5-13.

Govoreanu R., Nopens I., De Clercq B., Saveyn H., Van der Meeren P. and Vanrolleghem P.A. (2001). Influence of experimental parameters for on-line determination of floc size distribution. In: *Proceedings 12th Romanian International Conference on Chemistry and Chemical Engineering*. Bucharest, Romania, September 13-15 2001.

Law D.J., Bale A.J. and Jones S.E. (1997). Adaptation of focused beam reflectance measurement to in-situ particle sizing in estuaries and coastal waters. *Marine Geology,* **140**, 47-59.

Li D. and Ganczarczyk J. (1991). Size distribution of activated sludge flocs. *Research Journal WPCF,* **63**(5), 806-814.

Metcalf & Eddy, Inc (1991). Wastewater Engineering: Treatment, Disposal, Reuse. *McGraw-Hill International Editions (3th ed.), Civil Engineering Series*.

Monnier O., Klein J.-P., Hoff C. and Ratsimba B. (1996). Particle size determination by laser reflection: methodology and problems. *Part. Part. Syst. Charact.,* **13**, 10-17.

Nopens I., Biggs C.A., De Clercq B., Govoreanu R., Wilén B.-M., Lant P. and Vanrolleghem P.A. (2002). Modelling the activated sludge flocculation process combining laser light diffraction particle sizing and population balance modelling (PBM). *Wat. Sci. Tech.,* **45**(6), 41-49.

Parker D.S. (1970). *Characteristics of biological flocs in turbulent regimes*. PhD thesis, University of California, Berkeley, USA, pp. 156.

Peng S.J. and Williams R.A. (1993). Control and optimisation of mineral flocculation and transport processes using on-line particle size analysis. *Mineral Engineering,* **6**(2), 133-153.

Phillips J.M. and Walling D.E. (1995a). Measurement in situ of the effective particle-size characteristics of fluvial suspended sediment by means of a field-portable laser backscatter probe: some preliminary results. *Mar. Freshwater Res.,* **46**, 349-357.

Phillips J.M. and Walling D.E. (1995b). An assessment of the effects of sample collection, storage and resuspension on the representativeness of measurements of the effective particle size distribution of fluvial suspended sediment. *Wat. Res.,* **29**(11), 2498-2508.

Richmond W.R., Jones R.L. and Fawell P.D. (1998). The relationship between particle aggregation and rheology in mixed silica-titania suspensions. *Chem. Eng. J.,* **71**(1), 67-75.

Sparks R.G. and Dobbs C.L. (1993). The use of laser backscatter instrumentation for the on-line measurement of the particle size distribution of emulsions. *Part. Part. Syst. Charact.*, **10**, 279-289.

Spicer P.T. and Pratsinis S.E. (1996). Shear-induced flocculation: The evolution of floc structure and the shape of the size distribution at steady state. *Wat. Res.*, **30**(5), 1049-1056.

Wahlberg E.J. (1992). Activated sludge bioflocculation: measurement, influencing factors, and physical enhancement. *Ph.D. thesis, Clemson University, Clemson, S.C.*

Williams R.A., Peng S.J. and Naylor A. (1992). In situ measurement of particle aggregation and breakage kinetics in a concentrated suspension. *Powder Technology*, **73**, 75-83.

Worlitschek J. and Mazzotti M. (2001). Choice of the focal point position using Lasentec FBRM. Submitted to *Part. Part. Syst. Charact.*