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THE EFFECTS OF MEDIA SIZE ON THE PERFORMANCE AND EFFICIENCY OF BIOLOGICAL AERATED FILTERS

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THE EFFECTS OF BAF MEDIA SIZE ON PERFORMANCE

Abstract

Biological aerated filters (BAFs) are an attractive process option, particularly when low land usage is required. They can combine BOD, solids and ammoniacal nitrogen removal and can be utilised at both secondary and tertiary stages of wastewater treatment. Media selection is critical in the design and operation of BAFs to achieve effluent quality requirements. Two size ranges, 1.5-3.5 mm and 2.5-4.5 mm, of a foamed clay called StarLight C were used in pilot-scale reactors. Both performed well as BAF media, with reactor loads up to 12 kg COD m^{-3} d and 4 kg suspended solids m^{-3} d. (based on working volumes).

The most consistent effluent was obtained using the smaller medium since, at flow rates above 0.4 l min^{-1}, the BAF using the larger medium produced an effluent containing more than 20 mg l^{-1} of suspended solids for over 30 minutes after backwashing. Up to 70% longer run times, as determined by reaching a set head loss, were recorded for the BAF containing the larger rather than the smaller medium. Additionally, the development of pressure above the smaller medium filter bed tended to be logarithmic rather than linear. Reactor profiles indicated that suspended solids removal did not occur over the full 2.3 m depth of the columns. The BAF containing the smaller medium utilised a mean depth of 1.7 ± 0.3 m, whereas a mean depth of 2.1 ± 0.3 m was used by the larger medium BAF. Both the head loss development data and the suspended solids removal profiles indicated that the smaller medium BAF was underperforming as a filter.

Keywords

Biological aerated filter (BAF), head loss, media size, solids removal

INTRODUCTION

Biological aerated filters (BAFs) are flexible reactors which provide a small footprint process option at various stages of wastewater treatment. True BAFs, as defined by Stephenson (1997), contain a granular medium that provides a large surface area per unit volume for biofilm development. The medium also allows the reactors to act as deep, submerged filters and incorporate suspended solids removal. As a fixed-film process, optimal conditions for the relevant micro-organisms can be maintained independently of hydraulic retention times. The process has therefore achieved high levels of nitrification, denitrification and phosphate uptake (Goncalve & Rogalla, 1992).

The selection of a suitable BAF medium is critical in the design and operation of the process, to enable the required effluent standards to be reached. Superior substrate removal has been shown by BAFs containing mineral media, such as expanded clay, compared to those using sand or plastic media with similar dimensions (Moore *et al.*, 1999a). The size of a BAF medium also has a strong influence on process performance. Consequently, different sized media have been recommended for different applications (Mendoza-Espinosa & Stephenson, 1999). A medium larger than 6 mm may be preferable for a roughing stage BAF prior to full secondary treatment. Meanwhile, it has been suggested that a tertiary treatment BAF should use a medium smaller than 3 mm. The intermediate size range of 3 to 6 mm has been designated suitable for secondary treatment BAFs. However, within this mid-range, media with different mean hydraulic sizes will infer different operational constraints on the BAF process.

The performances of pilot-scale downflow BAFs, using four size ranges of the mineral medium Lytag, have been compared (Smith *et al.*, 1999). All except one of the samples of Lytag had a mean hydraulic size between 3 and 6 mm and so would have been considered suitable for a secondary treatment BAF. The results indicated that generally, for a given reactor to produce a particular effluent quality, media size dictates the maximum loading rate. The explanation is that a smaller medium offers a greater surface area per unit volume for biofilm development, and so minimises the required reactor volume.

Using three variants of a vitrified clay medium with mean particle sizes between 2.8 and 4.4 mm, it was found that decreasing the size of a BAF medium increased its backwashing requirements (Stensel *et al*., 1988). This would have a negative effect on the reactor's operating costs and productivity. The backwashing procedure in a BAF is normally initiated when a limiting head loss has developed, as a result of deposited solids reducing the filter porosity.

Thus, previous work indicates that decreasing BAF media size improves the reactor's substrate removal performance but increases its backwashing requirements. However, the mechanisms which cause these changes remain unclear. In this study, to achieve a better understanding of the influences of media size, the performance of two size ranges of foamed clay have been analysed in terms of substrate removal, suspended solids removal kinetics, and maximum run times.

MATERIALS AND METHODS

Two identical PVC reactors were built, with a diameter of 0.2 m. This diameter was selected because wall effects are limited if a filter's diameter is more than fifty times the mean particle size. If the wall effects were significant, there would be a greater variance in head loss build up (Lang *et al*., 1993). The reactors had a downflow configuration, a height of 3.15 m and contained 0.3 m of gravel beneath 2 m of media. Moore *et al*. (1999a) gives full details of reactor set up and start-up procedure. The operating flow rates (Q) with corresponding hydraulic retention time (HRT), hydraulic loading rate (HLR) and organic loading rates are summarised in Table 1.

One reactor contained the cylindrical foamed clay StarLight C, with particle diameters ranging between 1.5 and 3.5 mm. Details of the characteristics of this medium and previous performance results can be found in Moore *et al.* (1999b). The other reactor used a larger StarLight C with particle diameters ranging from 2.5 to 4.5 mm. Since the cylinders were up to three times longer than they were wide, it was assumed both would be categorised as suitable for secondary treatment BAFs. The two media have similar physical properties in terms of acid solubility, dirt content and attrition levels. The larger version has an estimated sunken density of 1650 kg m^{-3} compared with 1500 kg m^{-3} for the smaller medium, and a packed voidage of 45% rather than 40%. However, since their estimated experimental minimum fluidisation velocities were similar, both media were backwashed with a liquid velocity of 45 m h^{-1}. Prior to operation, tracer studies were conducted on the BAF containing the larger medium, following the methods, conditions and analysis used previously for the smaller medium (Moore *et al*., 1999b). The results are shown in Table 2.

During the 76 days of operation, influent and effluent samples were taken regularly and the concentrations of suspended solids (SS), soluble and total chemical oxygen demand (sCOD and tCOD) and ammoniacal nitrogen (NH_3) were analysed using standard methods (APHA, 1992). Portable probes were used to measure the temperature, pH and dissolved oxygen concentrations. Ports, at intervals of 0.2 m from the base of the columns, allowed samples to be drawn at specific intervals so that substrate removal profiles could be examined. The BAFs were backwashed every 24 hours using the procedure reported previously (Moore *et al*., 1999a). Generally, samples were drawn at the end of the filter run, but occasionally, samples were also taken immediately after backwashing to examine the recovery of effluent quality.

Pressure transducers were attached to the BAFs and the pressure build up above the filter beds was recorded using a data logger. At each flow rate the reactors were left without backwashing for up to 72 hours to find the maximum run time before filter blockage.

RESULTS

Start-up was rapid for both BAFs and steady SS removal was shown after just three days (Figure 1). For the smaller medium reactor, mean SS removal was over 89% for the whole period (Table 3). This performance was consistent following backwashing and increases in the flow rate (Q), and only fell below 80% on day 69 (Figure 1) immediately after the flow rate was increased to 0.6 l min^{-1}.

By contrast, the effluent from the larger medium reactor had less consistent levels of solids. Although the effluent SS concentrations were generally below 20 mg l^{-1} at all flow rates, there were seven peaks above 25 mg l^{-1}, and the effluent contained over 30 mg l^{-1} of SS on days 16, 48, 53 and 76. Most of these troughs can be explained, since the effluents were sampled immediately after backwashing on days 9, 16, 33, 40, 48, 53, 61 and 69. The larger medium exhibited reduced SS removal after backwashing and the recovery time appeared to depend on the flow rate (Figure 2). At 0.3 l min^{-1} the effluent recovered within 10 minutes whereas at 0.4 l min^{-1}, recovery took over 30 minutes.

Both reactors reached stable sCOD removal on the third day of operation (Figure 3) and subsequently achieved an overall mean of approximately 70% removal with flow rates between 0.3 and 0.6 l min^{-1} (Table 3). The mean percentages of sBOD in the sCOD were 80% in the influent and 12% in the effluents. Therefore, the BAFs achieved a mean sBOD removal of 96%. In both BAFs, sCOD removal was not impaired after backwashing and any reductions in removal were related to an unusually high, or low, influent concentration.

Nitrification was first observed on day 20, and by day 37 the effluent ammoniacal nitrogen concentration was 0.1 mg l^{-1} from the smaller medium reactor and 3.7 mg l^{-1} from the larger medium reactor. Ammoniacal nitrogen removal did not stabilise, mainly because the influent concentration was highly variable (between 13.3 and 46 mg l^{-1}). The low ammoniacal nitrogen concentrations in the effluents on day 37 were only repeated on day 61, after influent concentrations dropped from above 40 mg l^{-1} to below 15 mg l^{-1}.

Performing paired t-tests on the effluent results during stable operation indicated that there were significant differences in the suspended solids, sCOD and the ammoniacal nitrogen concentrations of the two reactors (p-values <0.001, 0.03 and <0.001 respectively).

The reactors had approximately 0.85 m clearance above the media beds to allow head loss development during the filter cycle. The maximum run time at each flow rate occurred when the maximum head loss was reached. At all flow rates, the reactor using the larger medium had longer filter run times. However, the difference between the maximum run times of the two reactors decreased as the flow rate was increased (Table 4). When a flow rate of 0.3 l min^{-1} was applied, there was a period when both reactors operated without much increase in head loss, followed by a logarithmic rise in pressure (Figure 5). Meanwhile, when a flow rate of 0.4 l min^{-1} was applied, the head loss above the reactor containing the larger medium increased more linearly with time (Figure 6). With a flow rate of 0.6 l min^{-1} the head loss above both reactors increased linearly for a period before a logarithmic rise in pressure.

Plots of the SS concentrations (C) against reactor height (H) gave typical first-order curves which could be described by Equation 1.

$$-dC/dt = kC \text{ (or after integration: } \ln [C/C_0] = kt) \qquad (1)$$

Where C_0 is the influent SS concentration and k is the rate constant. The time (t) corresponds to: HA/Q where, A is the cross-sectional area of the reactor and Q is the volumetric flow rate. For a first-order relationship, plotting $\ln(C/C_0)$ versus height results in a linear regression line with a gradient (m) equal to kA/Q (Figure 7). The first-order constant (k or mQ/A) for SS removal was higher for the BAF using small StarLight C than the BAF using larger StarLight C (Table 5). The R^2 values for these graphs were consistently over 0.9, which validates the assumption of first-order kinetics.

When using the smaller medium, the majority of profiles indicated that only part of the filter was being utilised for SS removal. The mean active depth was 1.7 m and in the most extreme case, only the first 1.3 m of the filter bed removed SS before the concentrations stabilised (Figure 8). A greater proportion of the filter bed was used for SS removal in the BAF using the larger StarLight. In both reactors, there were no significant changes to the mean values of m, k or the depth of filter used for SS removal after the influent flow rate was increased.

DISCUSSION

The tracer studies for the BAF containing large StarLight were compared with those conducted previously under identical conditions using the smaller StarLight, expanded clay, sand and plastic media (Moore *et al.*, 1999b). This indicated that packed beds of the larger StarLight and the expanded clay medium have similar hydraulic properties. Although these two media are different shapes, packed beds of both have voidage levels of approximately 45%. On empty bed trials using these two media, the peak tracer concentration appeared before the theoretical hydraulic residence time (tHRT), indicating the occurrence of channelling. However, when tracer studies were conducted on an operating bed of the expanded clay just before backwashing, channelling was no longer apparent, due to re-compaction and biofilm growth closing the preferential channels. In conclusion, the tracer study results for large StarLight highlight that poor performance, especially immediately after backwashing, may result from preferential channelling. Meanwhile, the reactor containing the smaller StarLight showed better plug flow conditions, which improves nitrification and solids removal (Mann *et al*., 1995, Fdz-Polanco *et al*., 1994). Any further increases in the size of StarLight would probably increase the levels of mixing so that the flow through the reactor no longer approximated plug flow. Correspondingly, nitrification would deteriorate as observed when using 3-6 mm, compared to 2-4 mm, expanded schist (Paffoni *et al*., 1990).

The effluents contained consistently lower levels of organic matter than required by many consents. The medium with the smaller size range showed significantly better sCOD and ammoniacal nitrogen removal. Ammoniacal nitrogen removal is a good indicator of biological performance since nitrifying bacteria are easily out-competed by heterotrophic micro-organisms. Therefore in a fixed-film, plug flow reactor, nitrification only occurs once COD levels are low, at the base of the reactor when using a downflow configuration. The results suggest that COD penetrated deeper into the reactor containing the larger medium. Thus, a BAF containing the smaller medium would treat a greater mass of substrate per volume of reactor. However, it may be possible to obtain similar performance and reactor footprint using the larger sized medium, by increasing the media depth.

Both reactors showed improved COD removal when the flow rate was increased from 0.3 to 0.4 l min^{-1}. This could be accounted for by changes in the influent composition, which occurred at the same time as the flow rate was increased. Alternatively, the increased liquid velocity may have improved substrate transfer into the biofilm (Peladan *et al.*, 1996) and, by controlling the biofilm thickness, removed internal diffusion limitations (Lazarova & Manem, 1994). COD removal was not adversely affected by further increases in the flow rate. However, the lower ammoniacal nitrogen removal observed at 0.6 l min^{-1} indicates that biological performance would eventually decrease with increasing flow rate.

Effluent SS consent levels are often set at or below 35 mg l^{-1}. The mean concentrations for both effluents at all flow rates were below this concentration. However, the standard could be exceeded for over twenty minutes after backwashing the larger medium reactor. Backwash recovery times of up to 45 minutes have been reported previously and, in a multi-cell arrangement, significant effects on effluent quality can be avoided (Budge & Gorrie, 1996).

A full-scale BAF may have improved operability and show lower media washout rates using the larger sized medium because it would be easier to separate media particles from the backwash water. Additionally, with its longer filter run times, the BAF using the larger medium would be the most efficient reactor in terms of operating costs. In BAF facilities with numerous cells, run-times below 24 hours are desirable to minimise the possibility that several cells require backwashing simultaneously (Stensel *et al.*, 1988). Therefore, the smaller medium may be limited to applications where the liquid velocity is below 2.4 m h^{-1}.

As well as having different run times, the pattern of head loss development differed using the two sizes of media. The head loss development and SS profile results can be interpreted by assuming that similar filtration mechanisms operate in deep, submerged filters and BAFs. Solids are transported to the surface of depth filter media grains by a combination of interception, diffusion and sedimentation (Bouwer, 1987). Deep bed filters are said to ripen because their performance improves initially during operation, as particle deposition increases the apparent filter grain size and reduces the filter porosity (Choo & Tien, 1993). In BAFs, this process will be combined with the metabolism of suspended matter and biofilm growth (Takahashi *et al.*, 1969). Head loss development occurs in deep, submerged filters as deposited solids reduce the filter porosity.

Efficient deep, submerged filters exhibit linear head loss development, and block when the solids holding capacity is reached. Backwashing is required either at this time, or when the head loss profile causes air pockets to develop in the lower regions of the filter. Air pockets effectively block pores, causing an increase in local flow rates and subsequently a decrease in filtrate quality (Ives, 1969). Solids are removed throughout the depth of an efficient deep filter, and the reaction can be characterised by a first-order equation. Meanwhile, under-performing filters remove smaller proportions of solids in each successive layer of media. Prior to reaching the solids holding capacity, the porosity at the top of such filters has been reduced sufficiently to induce physical straining. This causes the rapid production of a surface mat of deposit, and subsequently there is a logarithmic rise in head loss with time (Ives, 1969). Under-performing filters are undesirable since they require more frequent backwashing and have higher operating costs without offering any advantages.

At flow rates of 0.3 and 0.4 l min^{-1}, the SS removal profiles indicated that the BAF using the smaller medium was under-performing as a filter. Solids were not removed throughout the filter depth, so it is unlikely that the filter's solids holding capacity was ever reached. Additionally, the reactor showed a tendency for logarithmic rather than linear head loss development. It is likely that the under-performance of the smaller StarLight as a depth filter medium was part of the reason that shorter run times were recorded.

There appears to be a complex relationship between the influent characteristics and flow rate, the reactor height and media size, and the performance in terms of both effluent standards and operating costs. The topic warrants further investigation to determine optimal media sizes for different conditions. Dual media BAFs also have potential since they could combine the high performance properties of smaller media with the lower operating costs associated with larger media. This may be particularly successful using foamed clay, since the particle density can be controlled so that a layer of larger medium could be maintained above a layer of smaller medium.

CONCLUSIONS

1. Using either of the size ranges of StarLight C, the BAFs produced effluents with mean concentrations of SS and COD within most consent levels, at loadings over 12 kg tCOD m^{-3} d and 4 kg SS m^{-3} d. (based on working volumes).

2. The BAF utilising the smaller medium exhibited up to 70% shorter maximum run times than the BAF using the larger medium. The hydraulic loading of the small medium reactors may need to be restricted to below 2.4 m h^{-1} to prevent units requiring simultaneous backwashing. Additionally, the larger medium will be easier to separate from backwash water, which may improve process operability and reduce media washout.

3. The SS profiles and head loss development graphs indicated that the smaller medium was frequently exhibiting inefficient depth filtration. This partly explained the differences in filter run times and is highly undesirable.

4. The larger sized medium showed some inconsistency in SS removal immediately after backwashing at flow rates over 0.3 l min^{-1}, and inferior nitrification results. It is unclear whether this was due to the reactor having a decreased surface area per unit volume or a higher degree of mixing.

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Table 1: Summary of the operating parameters for the two pilot-scale BAFs

Flow rate ($l\ min^{-1}$)	**Day**	**Medium size range (mm)**	**HRT (mins)**	**HLR (mh^{-1})**	**Organic Loading Rates (kg m^{-3} d)***			
					tCOD	**sCOD**	**SS**	**NH_3**
0.3	1-40	1.5-3.5	96	1.4	4.9	2.1	1.8	0.4
		2.5-4.5	108	1.3	4.4	1.9	1.6	0.4
0.4	40-61	1.5-3.5	72	1.9	8.1	2.9	2.6	0.6
		2.5-4.5	81	1.7	7.2	2.6	2.3	0.5
0.5	61-69	1.5-3.5	58	2.4	7.9	2.7	2.6	0.7
		2.5-4.5	65	2.1	7.1	2.4	2.3	0.6
0.6	69-76	1.5-3.5	48	2.9	13.7	5.7	4.6	1.1
		2.5-4.5	54	2.5	12.2	5.0	4.1	0.9

* based on working volumes of the reactors

Table 2: Empty bed tracer study results for the larger StarLight with a particle size range 2.5-4.5 mm

Liquid flow rate ($l\ min^{-1}$)	**Air flow rate ($l\ min^{-1}$)**	**Hydraulic residence times (min)**			**Equivalent no. tanks (N)**
		theoretical	**mean**	**peak**	
0.4	0	81	98	78	9
0.4	2	81	102	55	5
0.8	2	41	74	38	3

Table 3: Summary of the substrate removal performance for the two pilot-scale BAFs

	Small medium					Large medium				
Q (l min^{-1})	**0.3**	**0.4**	**0.5**	**0.6**	**Overall**	**0.3**	**0.4**	**0.5**	**0.6**	**Overall**
tCOD: % removal	78	88	87	86	**83 ± 10**	71	84	85	80	**77 ± 14**
Effluent (mg l^{-1})	62	44	41	63	**56 ± 22**	86	60	49	96	**77 ± 36**
sCOD: % removal	65	78	73	76	**70 ± 12**	64	74	69	70	**68 ± 12**
Effluent (mg l^{-1})	48	30	29	46	**41 ± 16**	50	35	34	56	**45 ± 17**
SS: % removal	91	93	95	89	**92 ± 7**	82	87	94	83	**85 ± 13**
Effluent (mg l^{-1})	10	10	5	16	**10 ± 7**	20	17	8	22	**19 ± 13**
NH_3: % removal	33	63	62	58	**47 ± 32**	28	50	62	38	**39 ± 26**
Effluent (mg l^{-1})	19	12	11	16	**16 ± 9**	20	15	12	22	**18 ± 8**

Note: Mean values are given at specific flow rates and means ± st.dev. for overall performance

Table 4: Mean maximum run times for reactors at each flow rate

Flow rate (lmin^{-1})	**Mean of 2 maximum run times (hours)**			
	Small medium	**Larger medium**	**Difference**	**% difference**
0.3	47	78	31	66
0.4	30	51	21	70
0.5	27	37	10	37
0.6	21	29	8	38

Table 5: Mean kinetic parameters of suspended solids removal

Medium	**Q (l min^{-1})** **[no. profiles]**	**m** **mean ± stdev**	**mQ/A** **mean ± stdev**	**Depth (m)** **mean ± stdev**	**R^2** **mean ± stdev**
Smaller StarLight	0.3 [5]	1.8 ± 0.5	62 ± 18	1.7 ± 0.4	0.96 ± 0.02
	0.4 [6]	1.5 ± 0.2	70 ± 11	1.7 ± 0.2	0.91 ± 0.05
	Overall	**1.7 ± 0.4**	**66 ± 14**	**1.7 ± 0.3**	**0.93 ± 0.04**
Larger StarLight	0.3 [6]	1.4 ± 0.2	42 ± 6	2 ± 0.4	0.96 ± 0.02
	0.4 [3]	1.1 ± 0.1	45 ± 4	2.2 ± 0.2	0.95 ± 0.03
	Overall	**1.3 ± 0.2**	**43 ± 6**	**2.1 ± 0.3**	**0.95 ± 0.03**

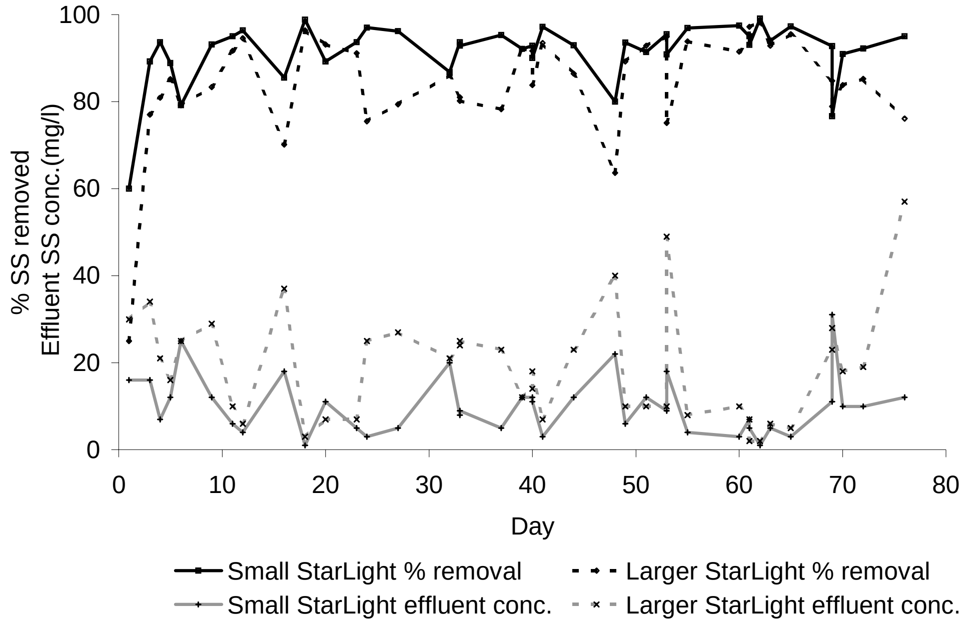

Figure 1: Suspended solids (SS) removal performance during operation

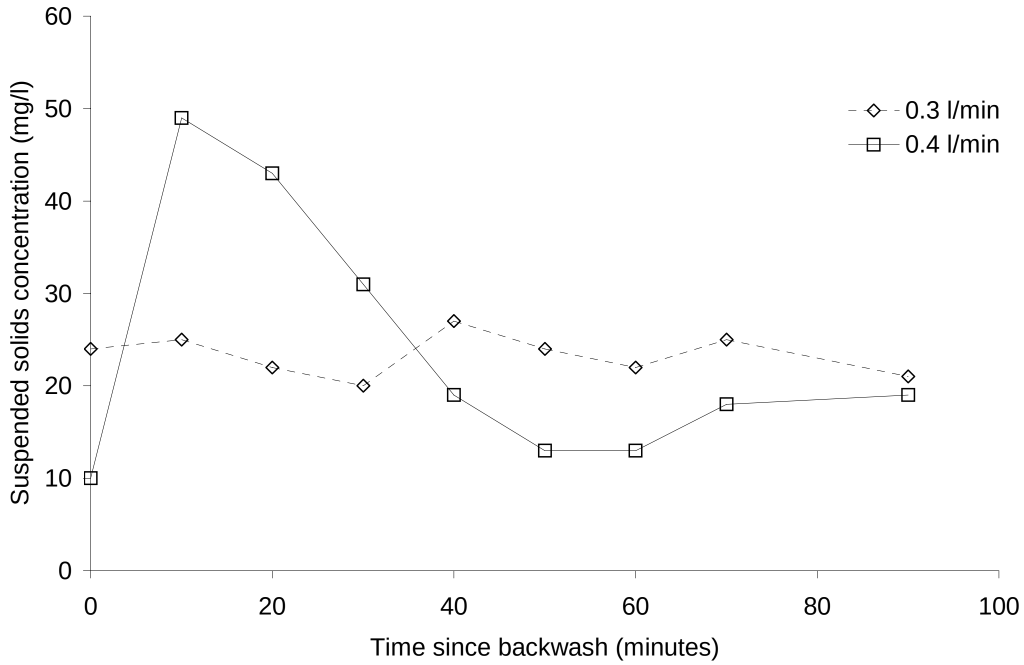

Figure 2: Effluent recovery after backwash in the BAF containing 2.5-4.5 mm StarLight at flow rates 0.3 and 0.4 l/min

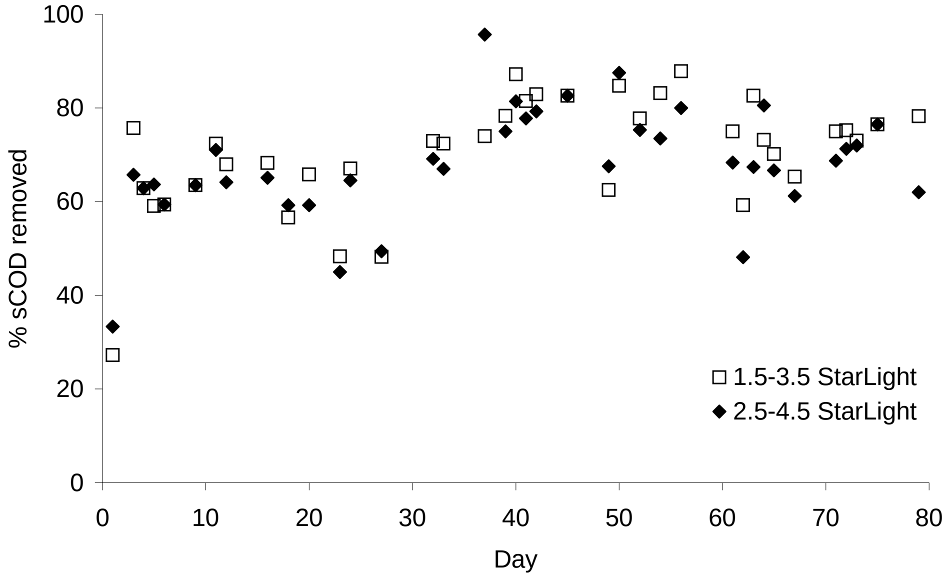

Figure 3: % removal of soluble chemical oxygen demand (sCOD) during operation

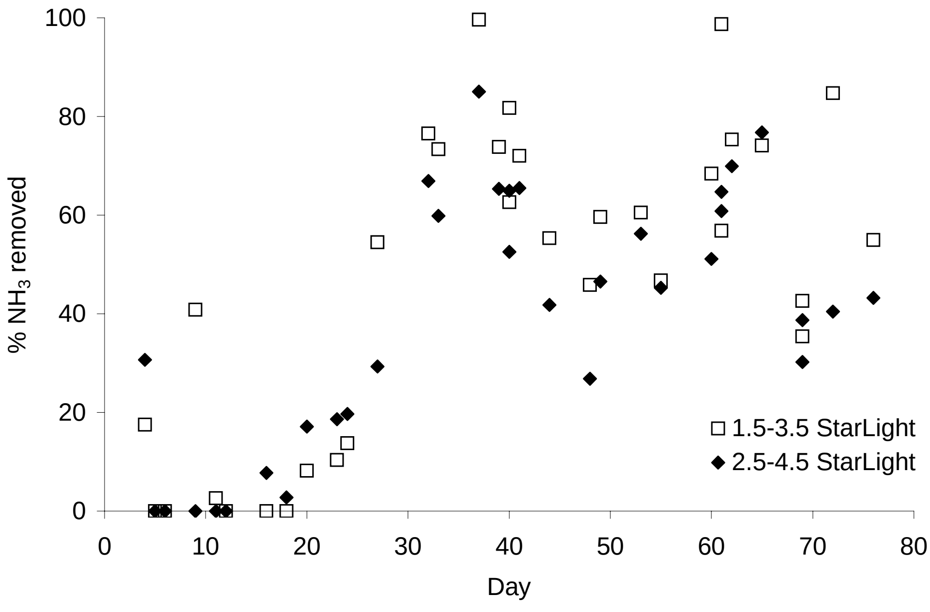

Figure 4: % removal of ammoniacal nitrogen (NH_3) during operation

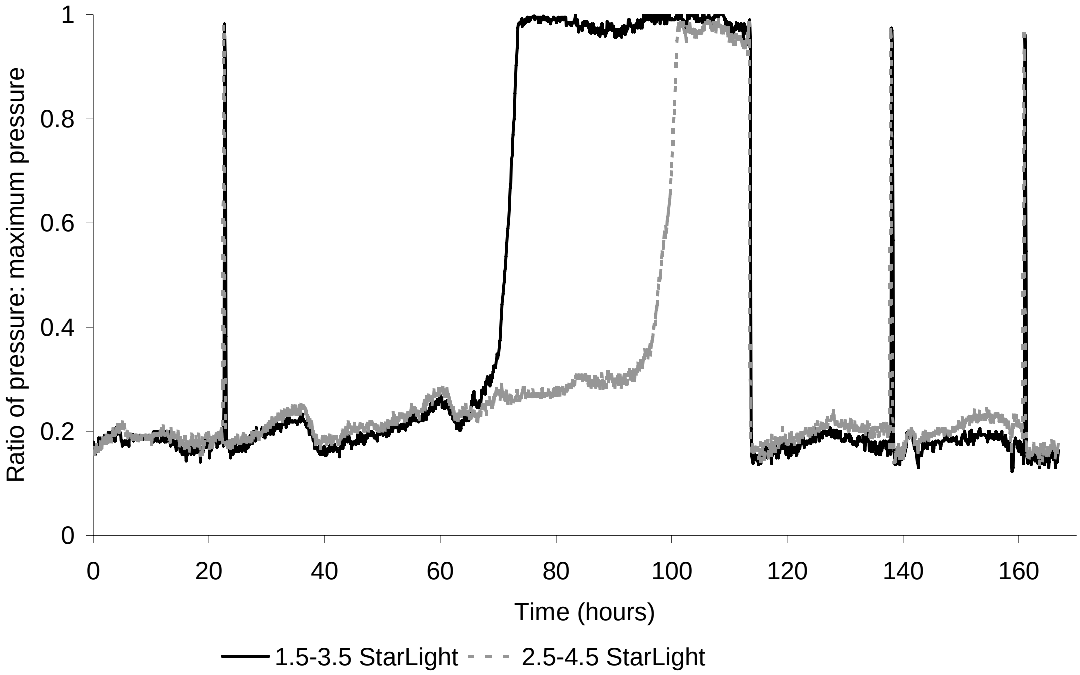

Figure 5: Pressure development with a flow rate of 0.3 l/min

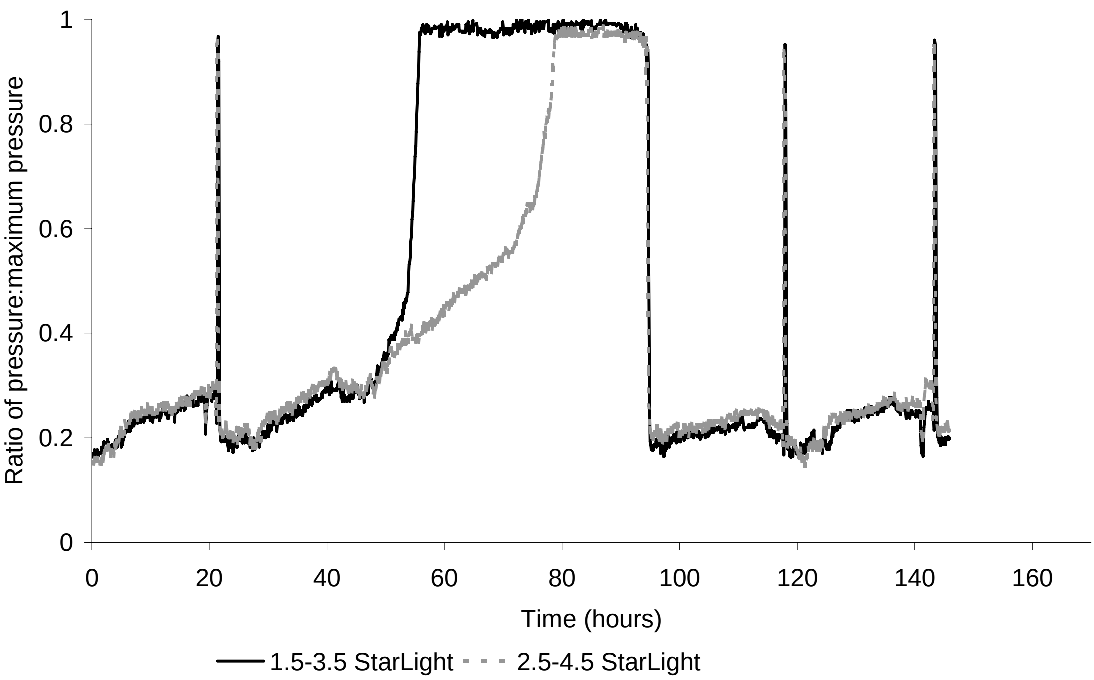

Figure 6: Pressure development with a flow rate of 0.4 l/min

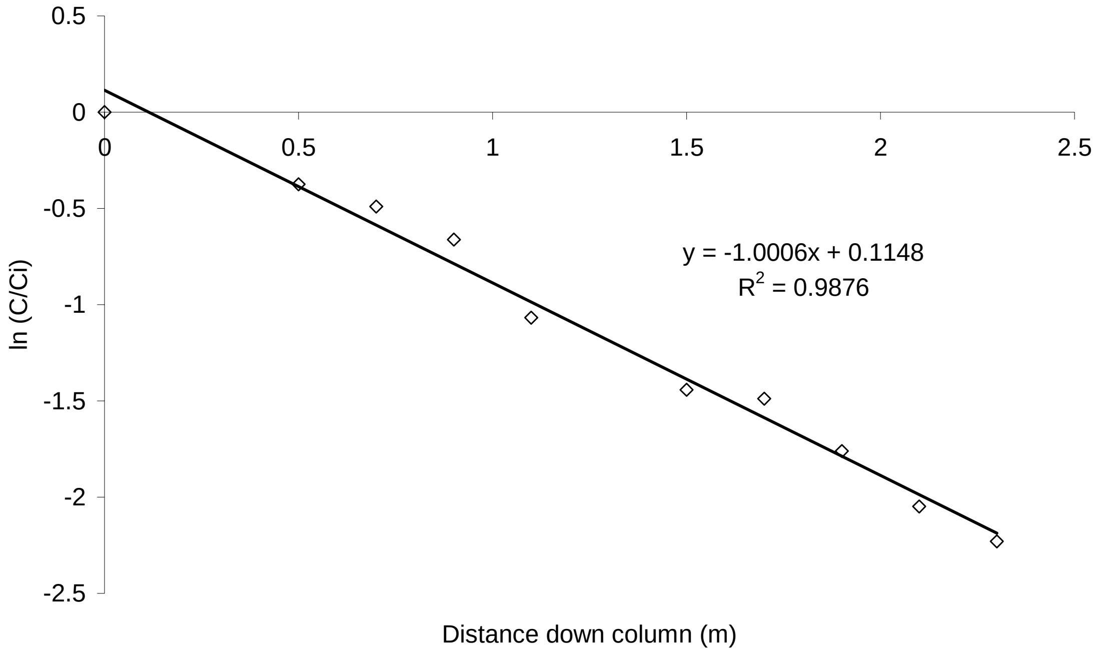

Figure 7: Logarithmic suspended solids removal profile using 2.5-4.5 mm StarLight with a flow rate of 0.4 l/min

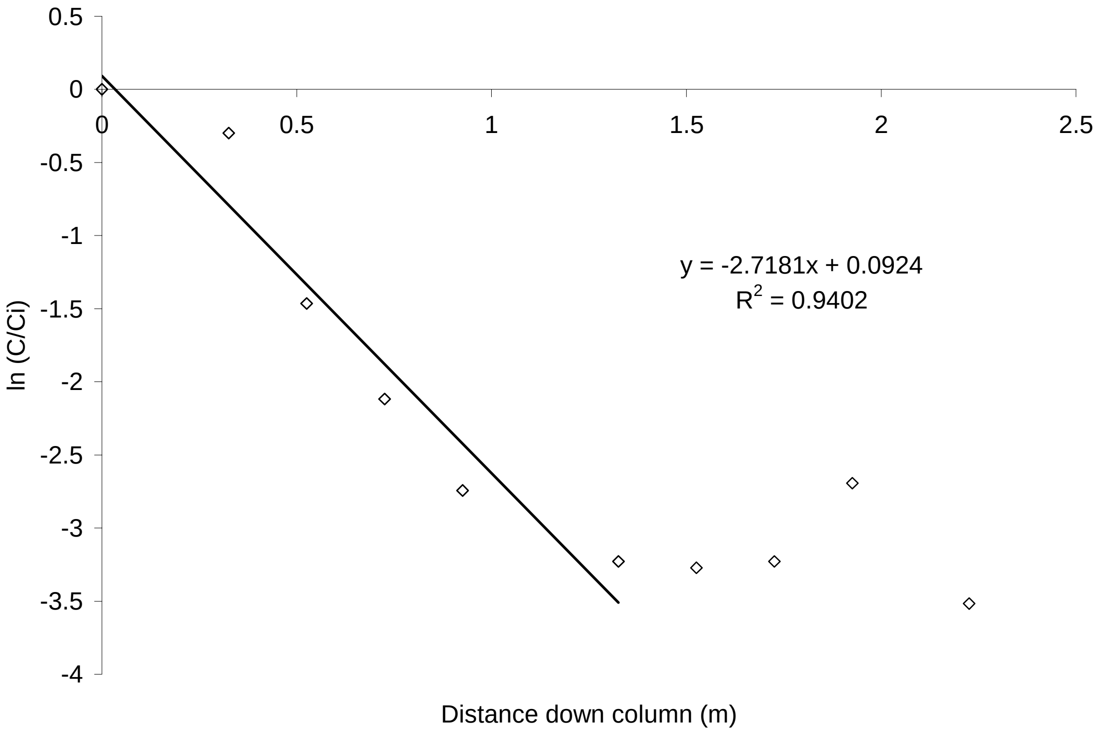

Figure 8: Logarithmic suspended solids removal profile using 1.5-3.5 mm StarLight with a flow rate of 0.3 l/min