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Novel microbial technologies for improved treatment of industrial wastewater

Pilot plant study

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1 INTRODUCTION

The meat processing industry requires large quantities of water, much of which is discharged as wastewater containing high levels of COD and nutrients such as nitrogen (N) and phosphorus (P). Over the past two decades, biological COD and N removal from abattoir wastewater has received much greater attention than has the biological P removal. Reliable biological COD and nitrogen removal systems have been successfully designed for abattoir wastewater treatment. However, P removal continues to be achieved **primarily through chemical precipitation, which incurs high costs for chemicals and for the handling** and disposal of the chemical sludge produced. Biological P removal is potentially a cheaper and more environmentally sustainable option.

One of the main obstacles for achieving Bio-P removal from abattoir wastewater is the high concentration of nitrogen in the wastewater (TN around 200 $g.m^{-3}$ or higher). When complete nitrification is achieved, which is a pre-requisite for a high-level removal of N, the equivalent level of nitrate formed is highly detrimental for Bio-P removal. Establishing anaerobic conditions in the treatment systems, which is required for Bio-P removal, is a significant challenge as nitrate needs to be removed completely before anaerobic conditions can be created. Denitrification will also compete with the Bio-P process for the limited amount of volatile fatty acids (VFA) present in the abattoir wastewater.

A previous MLA funded project (ENV.044) demonstrated the successful use of Sequencing Batch Reactor (SBR) technology at pilot-scale for achieving simultaneous N & P removal from abattoir wastewater. The three main measures taken to enhance Bio-P removal in the pilot-scale SBRs were:

- The wastewater feed was added to the reactor over three feeding periods in each SBR cycle. The multi-step feeding strategy keeps the nitrate concentration low throughout the SBR cycle, allowing easier creation of anaerobic conditions in the reactor;
- The UniFed® process (in which wastewater is fed to the bottom of the reactor) was applied to ensure localised anaerobic conditions develop in the sludge blanket to enhance anaerobic phosphate release and VFA uptake;
- An anaerobic prefermenter was included to ferment the raw wastewater at an elevated temperature to produce additional VFA. The VFA produced is added to the wastewater fed to the reactor, which is obtained from the effluent of an anaerobic pond. This type of pretreatment of the raw abattoir wastewater would typically be used upstream of an SBR process at full scale to reduce the high level of solids and other COD (including fat and oils) in the wastewater as it would otherwise heavily load the aerobic process and create high aeration costs.

The current project was aimed at increasing the SBR nutrient removal capacity through the use of aerobic granular sludge. Aerobic granular sludge plants have lower space requirements than conventional activated sludge systems and a higher nutrient conversion capacity due to a higher operating biomass concentration. They are also believed to generate substantially less waste sludge than conventional floccular systems.

The project aimed to characterise process parameters required for the conversion of activated sludge to aerobic granules suitable for bio-P removal from meat processing wastewater while simultaneously achieving high levels of removal for other components, notably chemical and/or biological oxygen demand (COD, BOD) and nitrogen.

More specifically, the project had the following objectives:

1. Determine key drivers for the conversion of floccular sludge to aerobic granular sludge;
2. Demonstrate aerobic granular SBR technology with a pilot plant operated under field conditions to achieve over 90% ammonia and ortho-phosphate removal from abattoir wastewater;
3. Achieve the above performance under typical load variations experienced by abattoir wastewater treatment plants through the use of on-line process control;
4. Investigate the interactions of nitrogen removal and biological phosphorus removal to ensure good, stable nutrient removal performance;
5. Investigate aerobic granule dewatering and sludge production properties.

2 PILOT-PLANT DESIGN

2.1 Past Experiences at the Site

The previous project (MLA project ENV.044) used a dual SBR rig located at Teys Bros. abattoir for the study of biological C, N and P removal from the site's wastewater. The rig consisted of two SBRs, each with a 6000L operating volume, attached to a hut which housed a PLC and other equipment.

The operating parameters of the SBRs are indicated in Table 2.1. Each cycle consisted of multiple feed and react periods prior to settling and decant. The feed consisted of a mix of prefermenter liquor (1.5 d HRT; typically 15-20% by volume) and anaerobic pond effluent (full-scale plant; typically 80-85% by volume).

Table 2.1: Operating parameters for previous study using floccular SBR.

HRT	42 hr
Cycle Length	6 hr
Feed vol./cycle	0.857 m^3
DO setpoints	1.5 $g.m^{-3}$
Combined Feed Characteristics	
Av. NH_4-N	191 $g.m^{-3}$
Av. NH_4-N Load	0.109 $kg.m^{-3}.d^{-1}$
Av. TN	234 $g.m^{-3}$
Av. TN Load	0.134 $kg.m^{-3}.d^{-1}$
Av. PO_4-P	32 $g.m^{-3}$
Av. PO_4-P Load	0.018 $kg.m^{-3}.d^{-1}$
Av. TP	34 $g.m^{-3}$
Av. TP Load	0.019 $kg.m^{-3}.d^{-1}$
Av. TCOD	1773 $g.m^{-3}$
Av. TCOD Load	1.013 $kg.m^{-3}.d^{-1}$
Av. Total VFA	184 $g.m^{-3}$ as VFA 263 $g.m^{-3}$ as COD
Av. TSS/VSS	771 $g.m^{-3}$/701 $g.m^{-3}$

The project was successful in achieving the aims of >90% TN and TP removal under the described conditions via simultaneous nitrification, denitrification and phosphorus removal (SNDPR), with denitrifying phosphorus accumulating organisms (PAOs) removing a portion of the NO_X-N. Greater than 90% TCOD removal was not achieved, largely due to some breakthrough of fat, oil and grease (FOG) from the DAF (via the prefermenter).

In the current project, the same pilot-plant was used with some modifications to allow for the development of biological granules and an increased load. The remainder of this section is a description of the pilot-plant, including modifications.

2.2 Pilot Plant Overview

Figure 2.1 shows a flow diagram of the pilot-plant. Continuous flow from the anaerobic pond (AP) flowed into the anaerobic pond overflow (APO/F) tank. A portion of this wastewater was used for the pilot-plant feed with the remainder overflowing into a waste tank.

Due to the low VFA concentration in the anaerobic pond effluent, a fraction of the raw wastewater from the site (exiting the DAF) was pumped intermittently into a prefermenter tank (PF). A portion of the PF wastewater was used for the pilot-plant feed with the remainder overflowing back to the DAF.

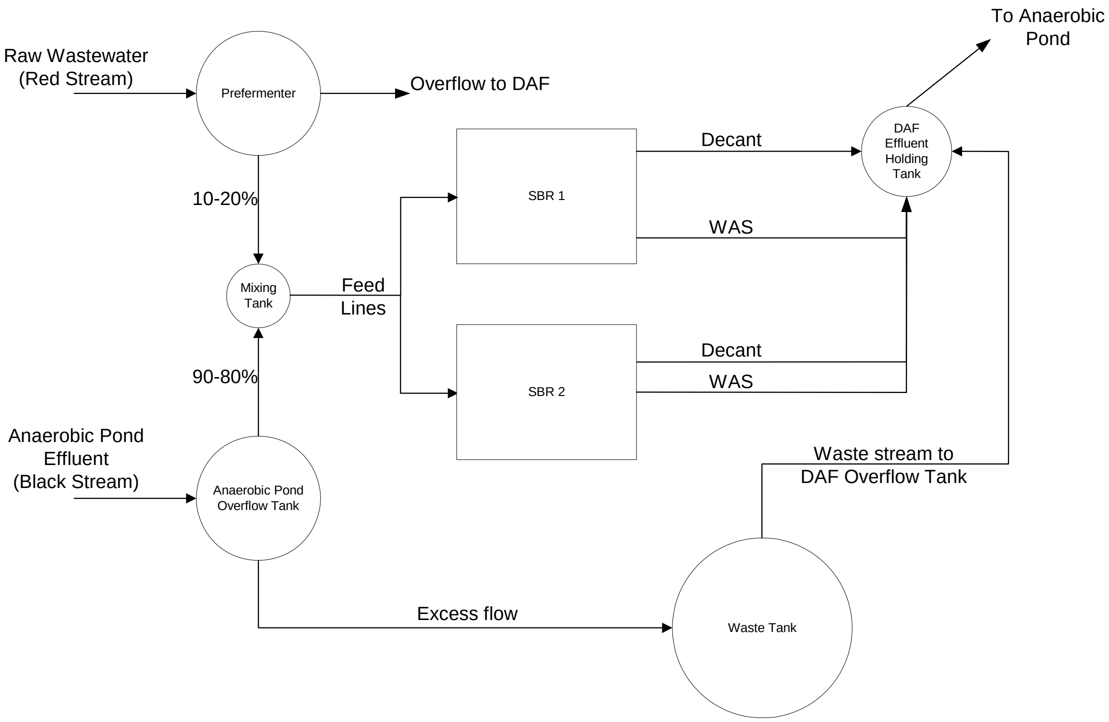


Figure 2.1: Flow diagram of pilot-plant.

Liquor from the anaerobic pond overflow tank and prefermenter (PF) were pumped into a mixing tank periodically. This feed mixture was pumped into asynchronously operated SBRs during feed periods in the cycles. The operating volumes of each SBR were 6 m^3.

The SBRs cycled through 3 phases of feeding/non-aerated period/aerated periods, followed by settle and decant periods. Sludge was only wasted at the beginning of the project while BNR performance was increased to a base loading rate. Subsequently, all sludge wastage occurred via the decant. Effluent from the SBRs was pumped during the decant periods to the DAF effluent holding tank of the main treatment plant. Waste which collected in the waste tank was pumped periodically (by submersible pump with float) to the DAF effluent holding tank for disposal.

2.3 Site Location

The pilot-plant was located at the Teys Brothers abattoir site, off Logan River Road, Holmview, near Beenleigh (Figure 2.2). Figure 2.3 shows the plant layout including piping. Various tanks were located on the concrete pad within a bunded area that accommodates the primary DAF for full-scale abattoir wastewater treatment. The actual pilot-plant SBRs were located outside the DAF bunded area on gravel within a small separate earth mound bund. This bunded area sloped to a sump which housed a submersible pump for transfer of surface runoff to the DAF effluent holding tank within the DAF bunded area. While the location was convenient for collection of the raw wastewater from the DAF, the Anaerobic Pond (AP) effluent needed to be transported by pipeline from the AP outlet over a distance of several hundred meters.

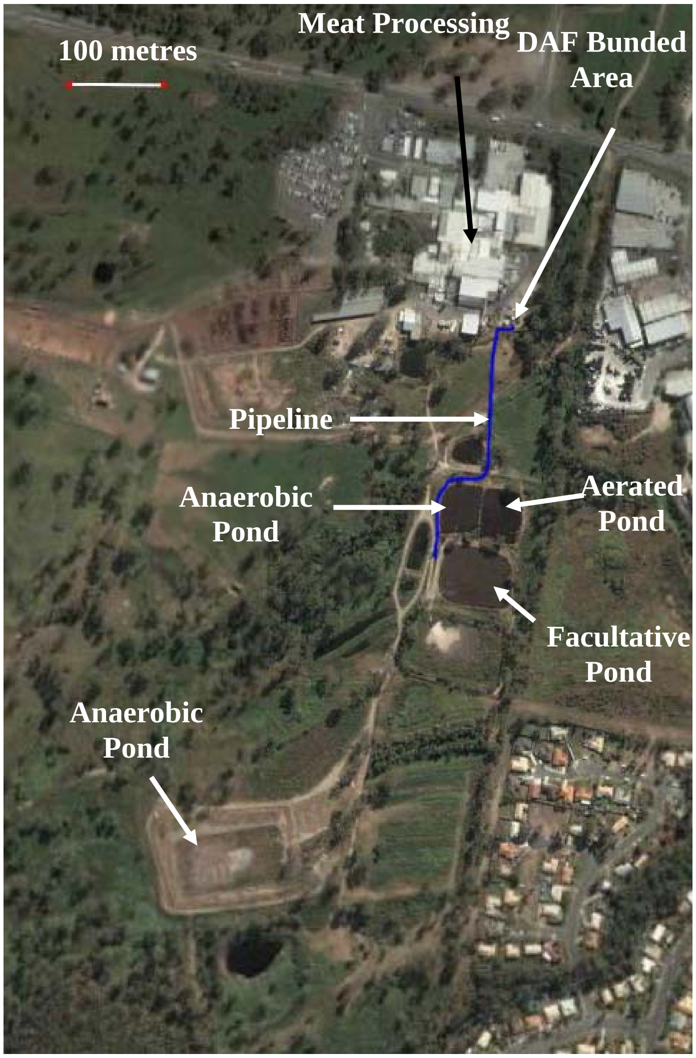
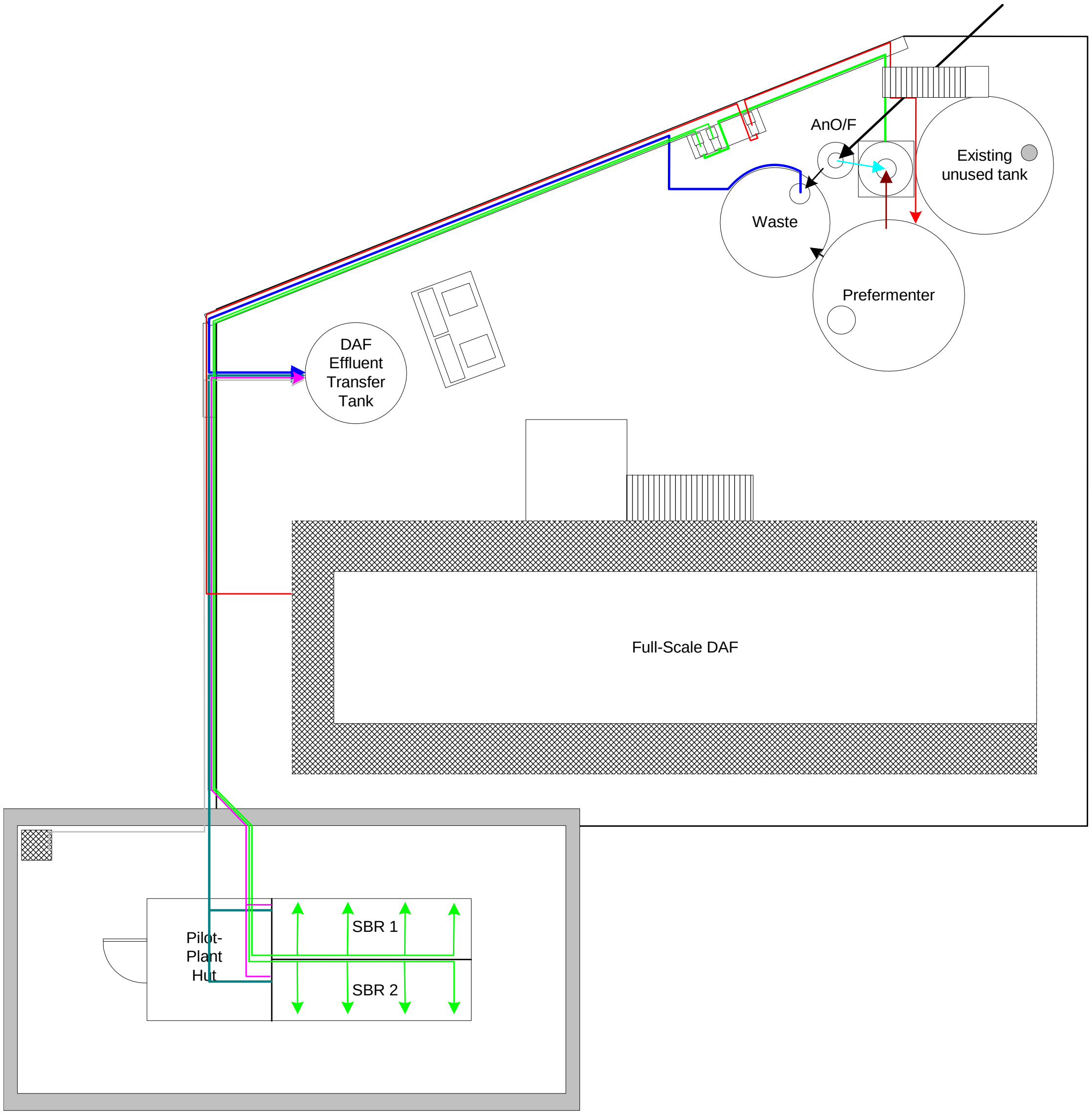


Figure 2.2: Teys Bros. Abattoir site showing anaerobic pond effluent pipeline to pilot-plant (Image Source: from Google Earth website).

A pump platform in the DAF bunded area supported the PF feed pump and the two SBR feed pumps. The pilot-plant hut housed the SBR waste activated sludge (WAS) pumps and blowers. The decant pumps were located externally next to the hut.



— Anaerobic pond effluent collection pipe

— Anaerobic pond effluent transfer pipe; flexible 1 inch pipe

— DAF effluent collection pipe; 1 inch uPVC pipe

— Prefermenter effluent feed collection pipe; flexible 1 inch pipe

— SBR feed pipe; 1.5 inch uPVC to pump and 1 inch uPVC from pump to SBRs (2 lines)

— WAS pipe; 1 inch uPVC pipe

— Decant pipe; 2 inch uPVC, connecting with sump pipe and waste tank discharge pipe

— Waste tank discharge pipe; 2 inch flexible from tank to cable and then 2 inch uPVC to connection with decant pipe

— Sump discharge pipe; 1.25 inch flexible pipe connecting to decant pipe

Figure 2.3: Pilot-plant layout.

2.4 Anaerobic Pond Effluent

2.4.1 Pipe Line

It is estimated the AP was located about 300 m away from the pilot-plant. The pond was at an elevated height compared to the pilot-plant. The extent of this rise was not known but estimated to be approximately 15 m.

The AP effluent flows over a weir into a pipe for gravity flow to the first aerated pond. The pipeline inlet for the pilot-plant tapped into this pipeline prior to the first aerated pond, thus reducing the distance of construction for laying of the pipeline to the pilot plant. A collection drum was located a short distance from the pipe take-off point (Figure 2.4). AP effluent flowed into the drum by gravity and continued down to the pilot-plant via a 50 mm ID polypipe. The flow of AP effluent was approximately 0.02-0.04 $m^3.min^{-1}$ and was continuous.

Figure 2.4: Pilot-plant take-off line and collection drum.

2.4.2 Anaerobic Pond Overflow Tank

The AP effluent exited the pipeline at the pilot-plant location into the anaerobic pond overflow tank (APO/F). The effluent entered the tank below the water surface to minimize the entrapment of oxygen into the liquid.

The APO/F was a polyethylene rainwater tank with dimensions 0.72 m diameter and 1.55 m wall height and an operating volume of 0.5 m^3 (operating height of 1.23 m, freeboard of 0.32 m). The small tank size was chosen to minimize the residence time of wastewater to ensure suspension of solids. No additional mixing was used in this tank. Excess flow from the tank overflowed into the nearby waste tank through a 100 mm diameter overflow pipe (Figure 2.5)

Figure 2.5: Anaerobic pond overflow tank, mixing tank and waste tank.

2.5 Prefermenter

The Prefermenter (PF) was used to supplement the insufficient VFA concentration in the AP effluent. The PF was a newly purchased 14 m^3 polyethylene rainwater tank (diameter 3 m, wall height 2.4 m) – the existing PF (from previous project) was too small for the expected larger feed volume. The tank had an overflow port for discharge to the DAF to maintain a constant operating volume of 12.5 m^3 and operating height of 1.835 m.

DAF effluent was pumped to the PF between the hours of 7am and midnight on weekdays only (full-scale plant shuts down over weekends and overnight). Flows varied depending upon the full-scale plant operation and desired HRT but were typically such that a weekday HRT of 1-1.5 d was maintained.

A submersible pump (30 $m^3.hr^{-1}$ flowrate) was located in the PF tank for periodic mixing. The pump was usually switched on for 10minutes after each feed preparation and then off at all other times.

A small submersible pump was located midway (vertically) in the tank for transfer of the prefermented liquor to the mixing tank.

2.6 Mixing Tank and Feed Preparation

The mixing tank (MT) was used to mix the two feed sources (PF and AP effluent). Initially the two feeds were mixed in the ratio of 80% AP effluent:

20% PF effluent. This ratio was subsequently altered throughout the project to achieve the desired VFA concentration in the feed (the PF was the main VFA source).
The MT was a polyethylene rainwater tank with dimensions of 1.07 m diameter and 1.51 m wall height (Figure 2.5). It was located on a 1m high platform due to possible flooding of the DAF bunded area. The maximum volume of feed which could be prepared at any one time was approx. 1 m^3. As the tank had a flat base, there was always a volume of mixed feed left in the tank following the feeding of an SBR (approximately 0.15 m^3).

Two Grundfos KP150 (single phase) submersible pumps were used to transfer the PF and AP effluents to the MT. The volumes pumped were critical and control of these was achieved using an on-line pressure transducer attached to the MT.

An on-line controlled submersible pump (Grundfos KP150, single phase) was placed in the MT and operated intermittently (during batch feed preparation) to mix the two feed streams and ensure no settling of solids occurred during the SBR feeding period.

2.7 Sequencing Batch Reactors

2.7.1 Rig Overview

The SBRs were located in an existing rig (owned by AWMC) used for previous pilot-scale studies. The rig comprised of two stainless steel tanks and a control room. The net weight of the pilot-plant is 4.6 tonne, has a total holding capacity of 16 m^3 in the tanks and has overall dimensions of 6.4 m (L) x 2.42 m (W). Each tank has dimensions of 3.91m (L) x 0.93 m (W) x 2.19 m (H), constructed with 3 mm thick, Grade 316 stainless steel. Both tanks were insulated and fitted with fourteen 0.9 m Aquablade diffusers (Aquatec Maxcon) for aeration.

The pilot-plant hut contained two Mono pumps (CP11; used as WAS pumps) and two positive displacement blowers. The blowers were connected to two variable speed drives (Toshiba VSF9 3.7 kW) and each has a maximum capacity of 164 $m^3.hr^{-1}$ at 50Hz. Sampling valves at varying heights on the tank sides were also located within the hut (Figure 2.6).

Two pH probes (Burkett #8205) and two differential pressure transducers were located in the hut, inserted into the tank sides. One DO transmitter (Danfoss #OXY3000) located in the hut was connected to two DO sensors (Danfoss OXY1100) inserted into tanks through the top. A process logic controller (PLC, Opto22 with Mistic Controller board), for controlling the whole pilot-plant, was also located in the hut.

Figure 2.6: Pilot-plant hut.

2.7.2 Pump Assignments

2.7.2.1 SBR Feed Pumps

Two Mono CP25 (single phase, max. flowrate of 0.025 $m^3.min^{-1}$) were located on a 1m high platform in the DAF bunded area to minimize suction distance (Figure 2.7). These were used for feeding the SBRs (from the MT).

2.7.2.2 Waste Pumps

Two Mono CP11 (single phase, max. flow 0.013 $m^3.min^{-1}$) were sited within the hut (Figure 2.8) and used as the waste pumps. The volume of wastage was measured by the on-line pressure transducers in each SBR.

2.7.2.3 Decant Pumps

Two centrifugal pumps for decanting were located outside the hut. The flowrate of these pumps was approximately 0.06-0.08 $m^3.min^{-1}$. The decant was wasted to the DAF effluent holding tank.

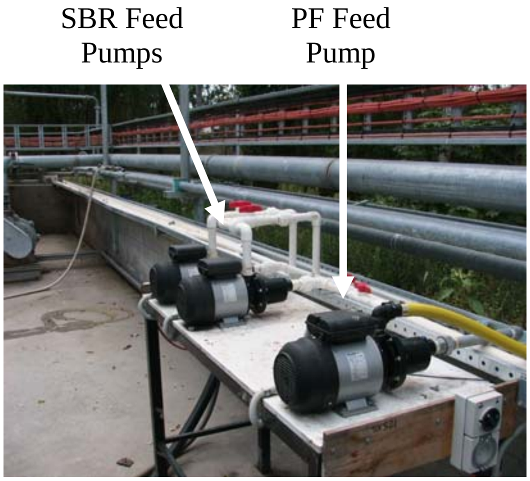


Figure 2.7: SBR feed pumps and prefermenter feed pump.

Figure 2.8: Location of WAS pumps in hut.

2.7.3 Tank Configuration and Aeration System

Due to the higher density of granules over floccular sludge, it was considered necessary to minimise the distance between the tank floor and the diffusers as the diffusers are the sole mixing mechanism in the tank. This was achieved by placing a water permeable liner (Geotex) over a layer of sand on the base of each tank (Figure 2.9).

Each SBR contained fourteen 0.9 m long Aquablade diffusers connected to a 100 mm diameter air supply pipe. The air supply pipe ran the length of the tank and exited perpendicular to the tank floor at the end adjacent to the hut.

The two blowers with PID control linked to two DO probes (see Section 2.7.4) provided the air requirements. Each SBR had its own independent aeration control system.

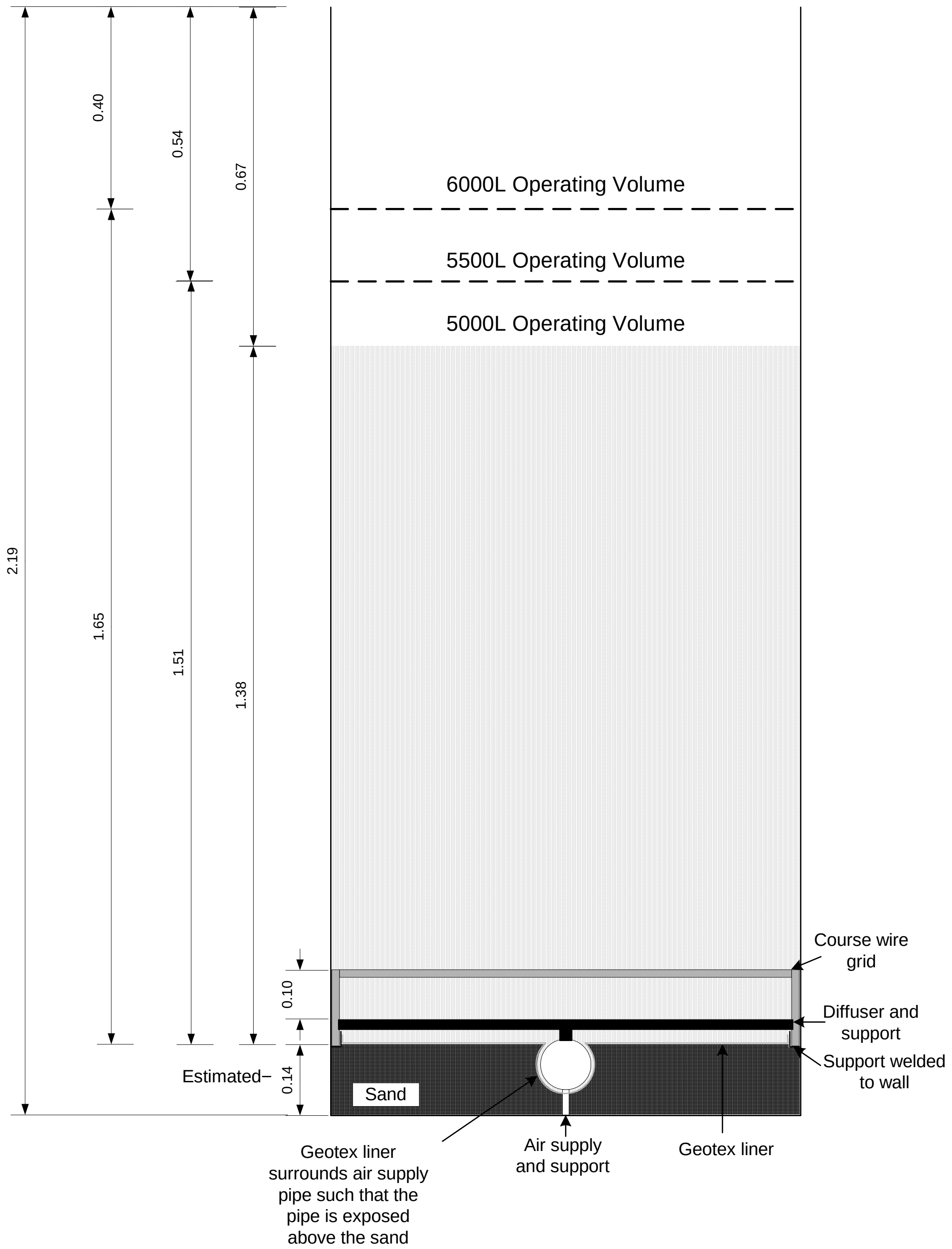


Figure 2.9: Tank configuration.

2.7.4 Sensors

DO, pH and pressure sensors were located in each SBR. Data was continuously logged by a computer attached to the PLC.

2.7.5 Operation of the SBRs

2.7.5.1 Feed Configuration

Both SBRs used the UniFed feed delivery system. This system involved evenly distributing the feed through the sludge blanket on the horizontal plane (Figure 2.10). This distribution was performed near the base of the tank (above the diffusers). No additional mixing was employed during the feeding period.

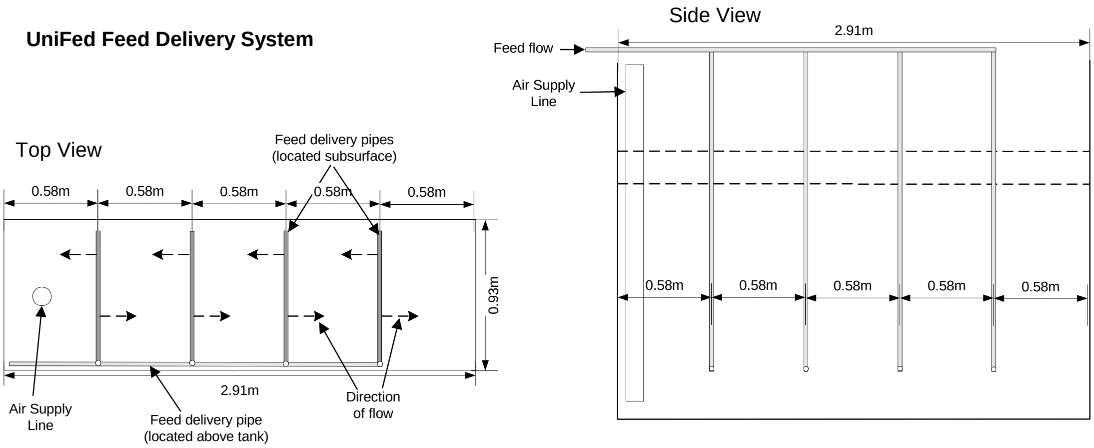


Figure 2.10: Unifed feed delivery system.

2.7.5.2 Cycle Periods

Table 2.2 shows the cycle periods and associated times used for commissioning of the SBRs. These periods were based on the results from the previous pilot investigation at Teys Bros. with the change of each anoxic and aerobic period being the same (previously, these changed over the three sub-cycles). Once a cycle had passed through all periods from settle to the third aerated period, the next cycle began at settle again. The times associated with these periods changed considerably throughout the project. Appendix 2 shows the cycle times when alterations were performed.

<u>Settle</u>
During the settling period, feed, WAS, decant pumps and blowers were switched off to allow the suspended solids/granules to settle, in preparation for decanting.

<u>Decant</u>
During decanting, the decant pumps (located outside the pilot-plant hut) pumped the supernatants to the DAF effluent holding tank. Initially the suction lines were simply pipes attached to floats (0.025 m^3 sealed drums) via flexible pipes, such that the pipe entrance was 200 mm below the surface level. This setup was later changed with the flexible pipe in each SBR connected to a 2 m length of 25 mm diameter pipe with 4 x 15 mm diameter holes spaced

evenly along the length. This pipe was submerged 0.4-1 m below the liquid surface in the centre of the tank to provide a multiple point submerged decant. The decant volume was measured with the on-line pressure sensors.
Table 2.2: Cycle periods for commissioning of pilot-plant.

Period	**Length**	**Purpose of Period**
Settle	30 min	Settle sludge
Decant	20 min	Remove supernatant
Feed 1	20 min	Add feed to reactor Residual denitrification P release by PAOs
Non-aerated period 1 (unmixed)	22 min	Residual denitrification Continued P release by PAOs
Aerated period 1	55 min	SND P uptake by PAOs
Idle 1	15 min	Depletion of residual DO
Feed 2	15 min	As for Feed 1
Non-aerated period 2 (unmixed)	22 min	As for Non-aerated period 1
Aerated period 2	55 min	As for Aerated period 1
Idle 2	15 min	As for Idle 1
Feed 3	15 min	As for Feed 1
Non-aerated period 1 (unmixed)	22 min	As for Non-aerated period 1
Aerated period 3	54 min	As for Aerated period 1
Total	360 min	

Feed Periods

Each SBR had 3 feed periods per cycle. At commissioning one fresh batch of feed was prepared and fed to both SBRs asynchronously per feed event. This was later changed with each feed period for each SBR prepared separately.

The feed (prepared as described in Section 2.6) was pumped into the SBRs by the feed pumps at a rate of approximately 0.025 $m^3.min^{-1}$. The total volumes fed into the SBRs were controlled by the on-line pressure transducer located on the side of the MT (this pressure transducer was chosen for control over the pressure transducers located on the SBRs as it was more accurate for small volume changes).

During the feed periods, not only was fresh feed added to the SBRs but also residual denitrification and P release by PAOs occurred.

Non-Aerated Periods

Following the feed period, the SBRs received a 30 second burst of aeration (blower output of 50%). Subsequently, a similar aeration burst occurred at 15min intervals until the end of the non-aerated period. These “mixing” events were important to mix the reactor contents and bring liquor from the upper water column (with possible NO_X species) into contact with the biomass.
The non-aerated periods were used for residual denitrification and also provided additional time for further anaerobic P release from PAO bacteria if required.

Aerated Periods and Sludge Wastage
During the aerated periods, the SBRs were aerated by the blowers through the diffuser systems described previously. The blowers were controlled by a PID loop coupled with the DO sensors for continuous operation. No additional mixing was provided during the aerobic periods. Initially a DO setpoint of 1.75 $g.m^{-3}$ was selected – this was later reduced to 1.5 $g.m^{-3}$.

The aim of the aerated periods was to achieve simultaneous nitrification and denitrification, largely via NO_2 (not NO_3 in order to conserve carbon). The previous pilot-plant study showed that the competition by denitrifying PAOs (DPAOs) was sufficient to limit the growth of nitrite oxidizing bacteria and it was possible to operate the SBRs with minimal NO_2 accumulation.

Sludge wastage from the SBRs, if required, occurred during the third aeration period of the cycle. Initially an SRT of 15 days for both SBRs was used. The suction lines for WAS pumps were located mid height of the SBRs. The wasted sludge was pumped to the Waste Tank.

Idle Periods
The idle periods were simply non-aerated periods which occurred after aeration periods to reduce the DO and develop a sludge blanket prior to feeding.

2.8 Waste Tank

The waste tank acted as a collection point for the APO/F and WAS. The waste tank had dimensions of 2.17 m diameter and wall height of 1.225 m. The maximum tank volume was 4 m^3 (maximum operating height of 1.08 m). A submersible pump (Lowara DOMO10, single phase) with float (i.e. not controlled by PLC) was used for emptying the tank to the existing on-site DAF effluent holding tank.

2.9 PLC Control

The pilot-plant PLC consisted of (all from Opto22):

- 1 G4LC32SX controller (with G4LC32ARC card and G4LC32SER card)
- 2 G4D16L bricks (each with 16 digital inputs/outputs; variable)
- 1 G4A8L brick (8 analog inputs/outputs; variable)

- 1 G4LAX brick (8 analog inputs/outputs; variable; extension of G4A8L)

3 RESULTS AND DISCUSSION

3.1 Commissioning

Each SBR was seeded with 5 m^3 of sludge collected from Thorneside Wastewater Treatment Plant on 16/4/08. Due to some mechanical issues, continuous operation was not achieved until 18/4/08. The initial startup HRT was 68.3 hr but this was rapidly decreased to 42 hr within 8 days. Sludge wastage commenced 6 days after startup and continued for 16 days while nutrient removal stabilized.

A 42 hr HRT was chosen as an initial base load starting point as this was the loading used in the previous project when excellent nutrient removal was achieved using floccular sludge. This was equivalent to a hydraulic loading rate of 0.57 $m^3.m^{-3}.d^{-1}$.

Within 3 weeks of startup, >95% NH_4 and PO_4 removal had been achieved in both SBRs. On 8th May 2008 changes were made to commence granulation of the sludge.

3.2 Feed Characteristics

Both SBRs received a mixed feed consisting of fractions collected from the full-scale anaerobic pond and the pilot-scale prefermenter. The proportion (by volume) of feed streams fed to the pilot plant is shown in Figure 3.1. Typically, the combined feed contained 10-20% prefermenter volume and 90-80% anaerobic pond effluent. Throughout most of the study, both SBRs received the same proportion of feed sources. Only on few occasions were these proportions different between the SBRs and in these cases the differences were very minor.

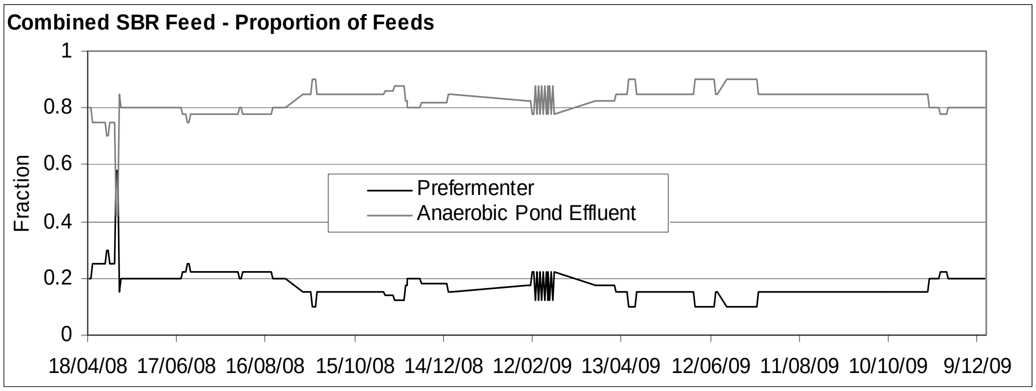


Figure 3.1: Feed proportions by volume for the SBRs.

3.2.1 Anaerobic Pond

The anaerobic pond serves as the primary treatment step in the mainstream abattoir wastewater treatment process, receiving both the “green stream” and the “red stream” (the latter after pre-treatment in the DAF). Despite relatively high loadings (partly due to poor operation of the DAF pre-treatment step), the pond appeared to perform very well during this study. The influent to the anaerobic pond was not measured as part of this project but based on previous studies was estimated to contain approx. 2500 to 4000 g.m^{-3} COD, 120 to 200 g.m^{-3} TKN and 20-40 g.m^{-3} Total P.

The data in Figure 3.2 show that the anaerobic pond effluent (overflow) contains a total COD of ~600 to 1400 g.m^{-3}, of which the soluble component is quite stable at around 160 g.m^{-3}. Hence the anaerobic pond probably achieved >65% COD removal, which is considered to be good for this type of system.

The total VFA concentration (Figure 3.3), expressed as COD by appropriate conversion for each of the measured VFA species (C2 to C6, i.e. acetic to hexanoic acid), averaged 17 g.m^{-3} COD (range 1-69 g.m^{-3}). On average, the acetic and propionic acids combined represented almost 90% of the C1-C6 acids produced and the acetic acid alone represented 71%.

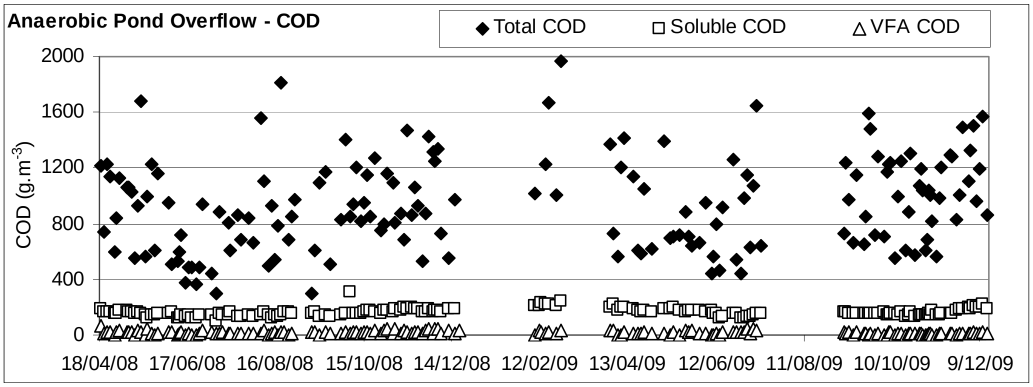


Figure 3.2: Anaerobic pond overflow COD trends.

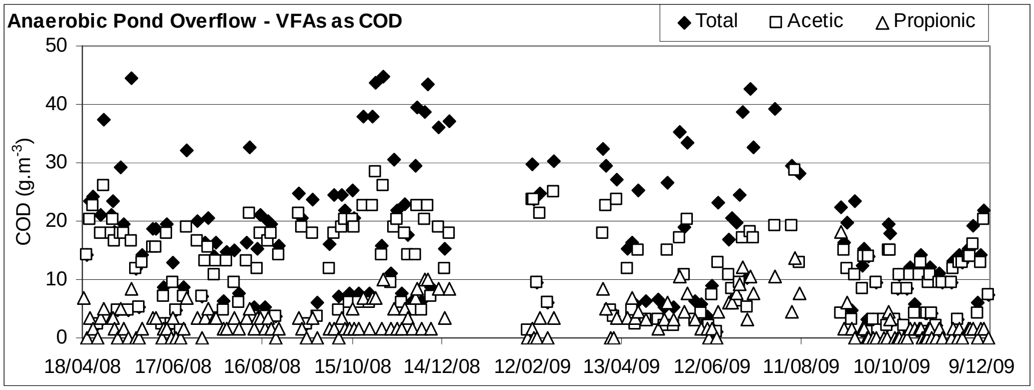


Figure 3.3: Anaerobic pond overflow volatile fatty acid trends.

The anaerobic pond effluent solids content is shown in Figure 3.4. The average TSS concentration was 620 $g.m^{-3}$ and ranged from 150-1620 $g.m^{-3}$. The average volatile content was 80% and the average median particle size, 62 µm diameter. The solids always appeared as black particulates.

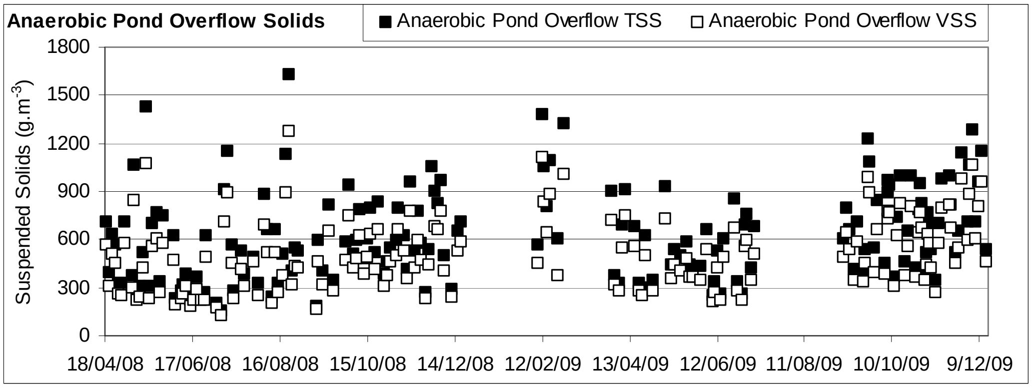


Figure 3.4: Anaerobic pond effluent solids.

The anaerobic pond effluent soluble ammonia and phosphate concentrations were relatively stable throughout most of the project (Figure 3.5). This was largely due to the estimated 5 day residence time in the pond. There is an observable seasonal variation which is likely due to seasonal fluctuations of the pond temperature. The anaerobic pond effluent temperature measurements shown in Figure 3.6 are for samples collected at the pilot-plant after travelling approximately 300m from the pond through a black pipe. Periodic measurements of the pond effluent prior to passing through the pipe show passage through the pipe typically increases the water temperature by 2-3ºC, depending upon the prevailing weather conditions.

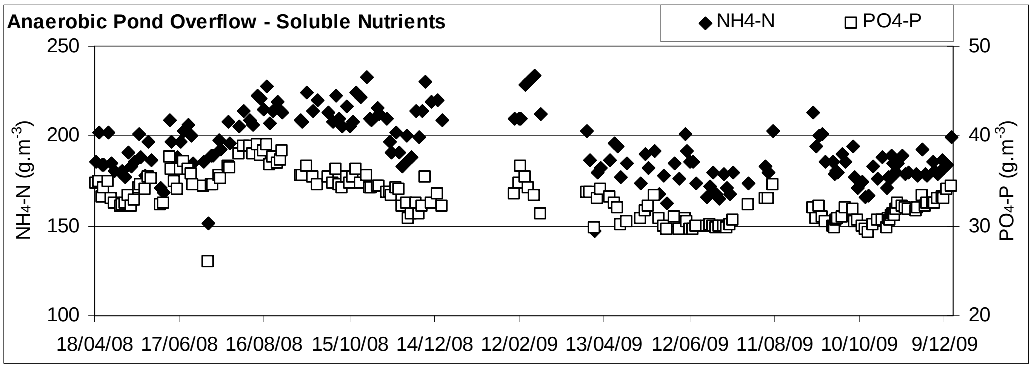


Figure 3.5: Anaerobic pond effluent soluble ammonia and ortho-phosphate.

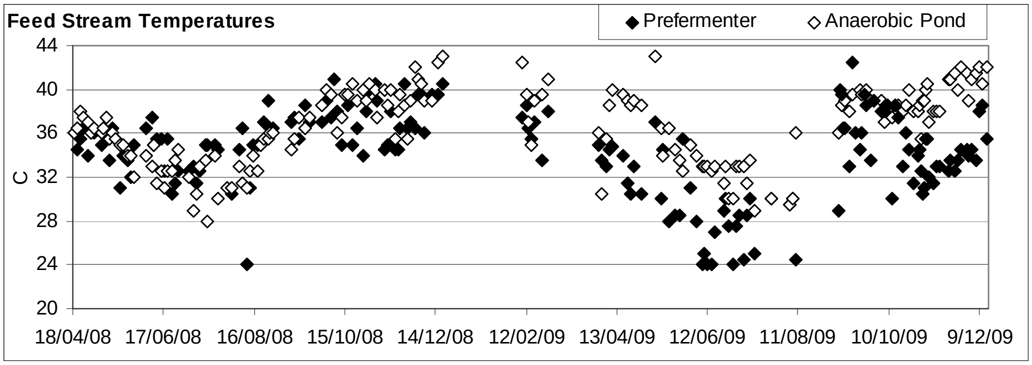


Figure 3.6: Pilot-plant feed stream temperatures.

3.2.2 Prefermenter

The prefermenter feed was collected from the end of the DAF which received the “red stream”. Recent alterations to the full-scale pre-treatment works resulted in the removal of the “save-all” which was present during the previous project. Subsequently, all “red stream” wastewater passed directly into the DAF, eliminating the pre-removal of a portion of the fats and solids upstream of the DAF. Exacerbating this was the high temperature of the wastewater entering the DAF (typically 45-50ºC), resulting in poor operational performance in terms of solids and fat removal (based on previous study measurements).

The prefermenter received an intermittent feed based on the availability of the feed source. The abattoir operates typically between 6am and midnight on weekdays, shutting down overnight and over weekends. This resulted in the intermittent feeding of the prefermenter between 7am and midnight on weekdays and no feeding from midnight Friday through to 7am Monday morning. The prefermenter was sized such that sufficient volume was available for feed preparation over weekends, drawing down some of the tank volume. Occasionally the abattoir would also shutdown on weekdays and when this occurred, feeding to the prefermenter was also stopped.

Figure 3.7 shows the 7 day moving average HRT of the prefermenter. In 2008, the prefermenter was typically operated with a weekday HRT of 1.5 days, resulting in a 7-day moving average of 2.6 days. In 2009, attempts to optimize the prefermenter were undertaken, which in part involved manipulation of the HRT, hence the variability observed for this year.

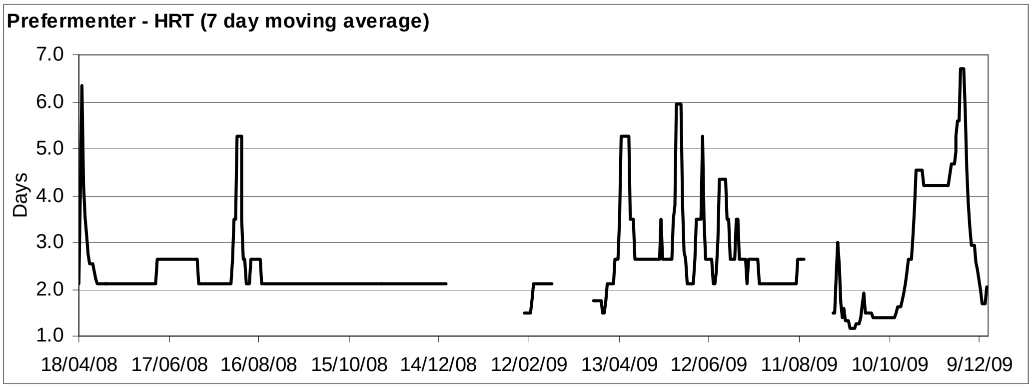


Figure 3.7: Prefermenter 7-day moving average HRT.

The prefermenter effluent COD is shown in Figure 3.8. The Total COD (TCOD) was highly variable throughout the project. This was largely due to variability in the effluent solids concentration (Figure 3.9) which was the result of no feeding over weekends (affecting early week grab samples) and changes to mixing regime. It is highly likely the fat content of the wastewater also affected settleability.

The COD fraction attributed to VFA (COD_{VFA}) and the Soluble COD (SCOD) were very stable. Table 3.1 shows statistical analysis of the COD fractions. The COD_{VFA} on average was 83% of the SCOD fraction, indicating most of the solublised COD was in VFA form. However, the COD_{VFA} represented only 37% of the TCOD, indicating the majority of the COD was in particulate form.

Table 3.1: Statistics of various COD parameters.

Parameter		Total COD	Soluble COD	COD_{VFA}	Sol. COD/ Tot. COD	COD_{VFA}/ TCOD	COD_{VFA}/ Sol. COD
Average	$g.m^{-3}$	4209	1499	1253	44.0%	37.3%	83.0%
Std. Dev.	$g.m^{-3}$	2581	248	309	17.6%	17.6%	14.3%

Min. g.m^{-3}	1368	722	347	7%	3.5%	17.4%
Max. g.m^{-3}	21885	2194	2213	88%	91.8%	100%
Count	171	169	174	169	169	167

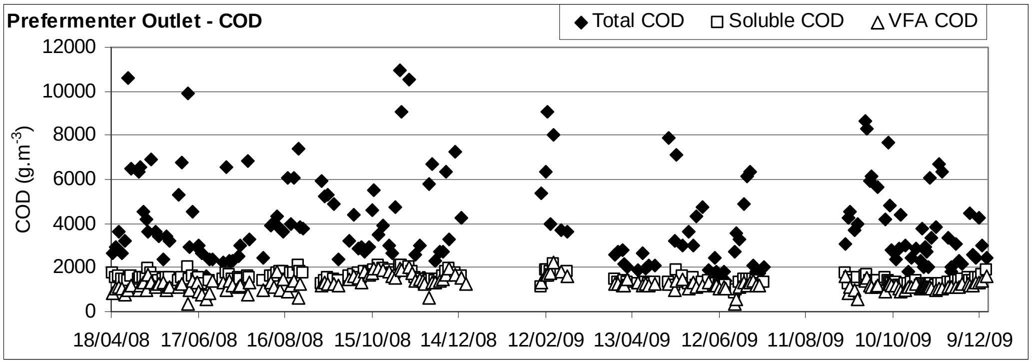


Figure 3.8: Prefermenter effluent COD trends.

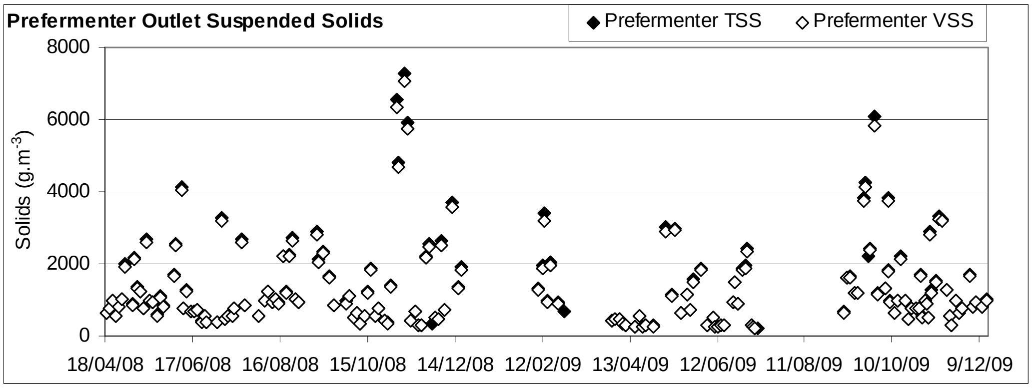


Figure 3.9: Prefermenter effluent solids.

The prefermenter preformed well in respect of VFA generation. Propionic acid was the dominant species, representing on average 39% of the total VFAs present (Figure 3.10). Acetic acid represented 25% of total VFAs with the remainder dominated by valeric (13.6%), iso-butyric (8.4%) and butyric (7.9%).

There was a correlation between prefermenter temperatures (Figure 3.6) and VFA concentration. Elevated prefermenter temperatures resulted in elevated VFA concentrations. Note – in September, 2009 HRT investigations (discussed in Section 3.3.4) resulted in elevated temperatures without elevated VFA concentrations and this can be explained by a reduced SRT of the sludge in the prefermenter.

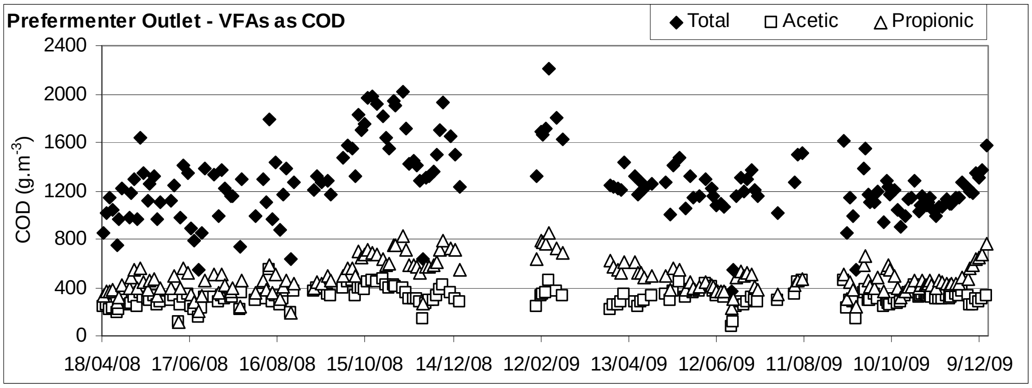


Figure 3.10: Trend of prefermenter outlet VFAs.

Figure 3.11 shows the ammonia and ortho-phosphate profiles for the prefermenter effluent. There appears to be a seasonal variation in the ammonia concentration which follows the trend in temperature shift (Figure 3.6). This is likely the result of variations in hydrolysis due to temperature shifts, with higher temperatures allowing for further hydrolysis.

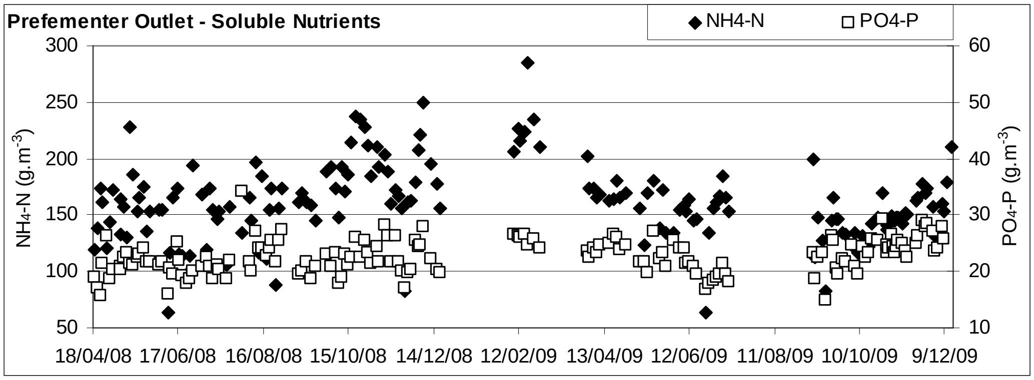


Figure 3.11: Prefermenter effluent nutrient profiles.

3.2.3 Loading to the Pilot-Plant

The volumetric and mass loadings to the SBRs for the combined feed concentrations (calculated from the measurement on the two individual streams and the programmed feed mix ratio) are shown in Figure 3.12 and Figure 3.13.

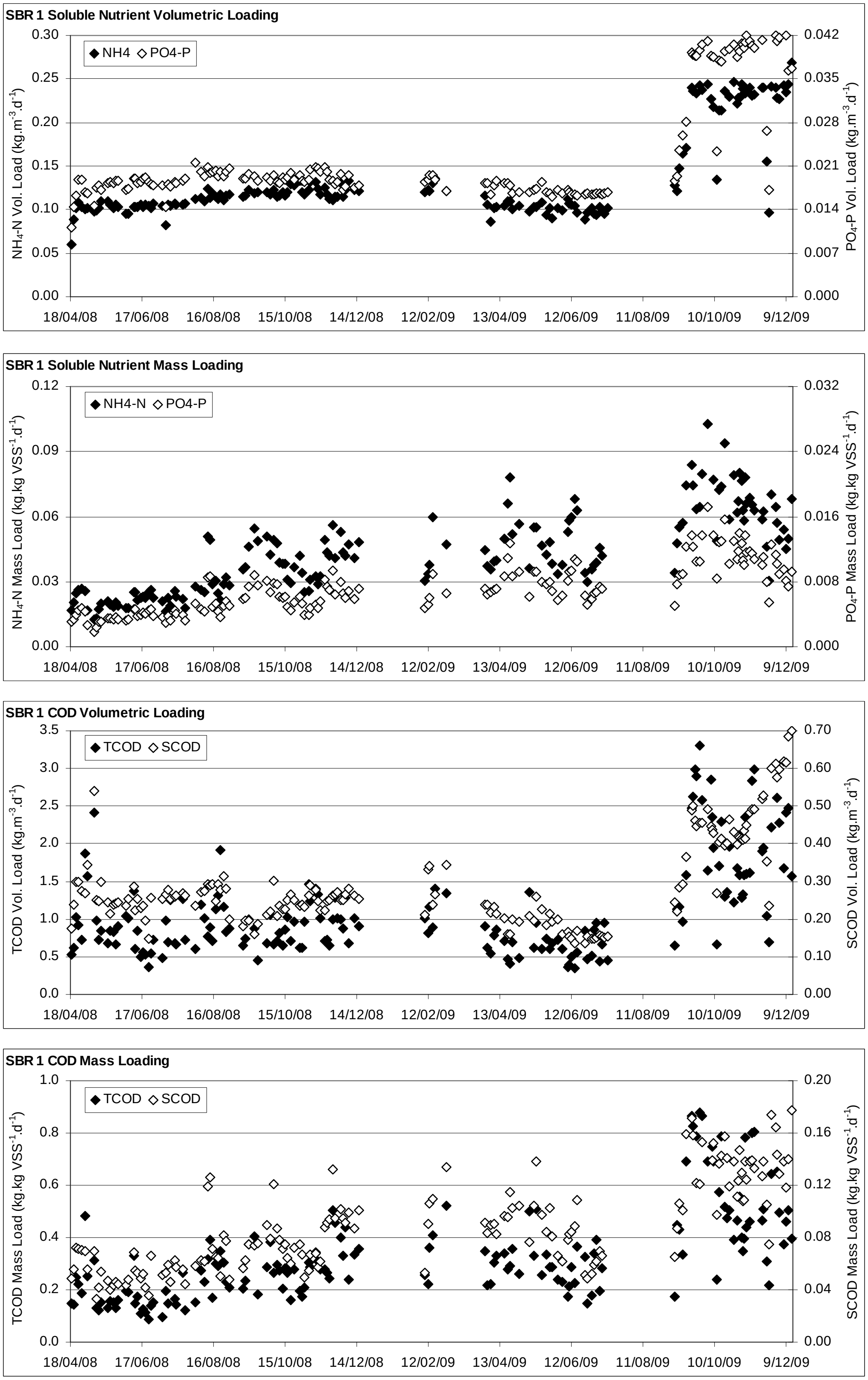
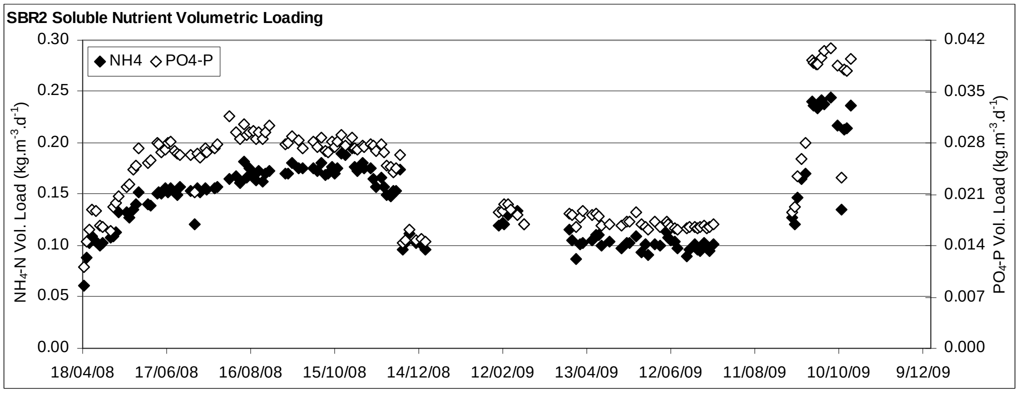
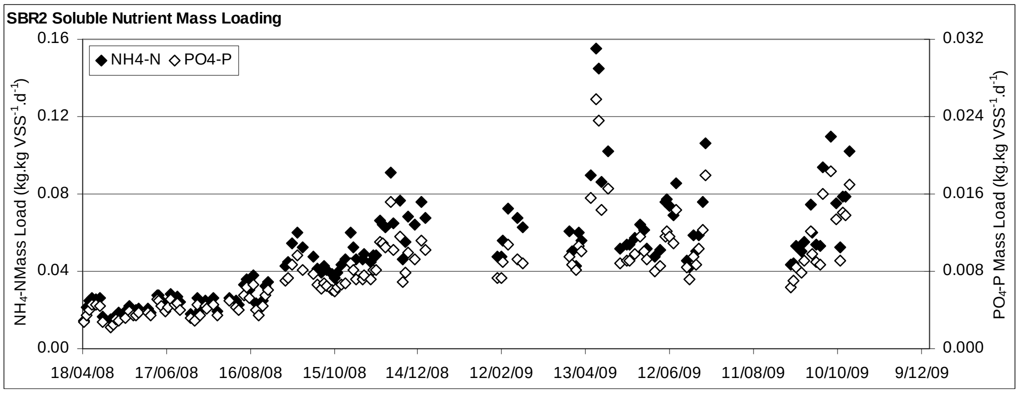
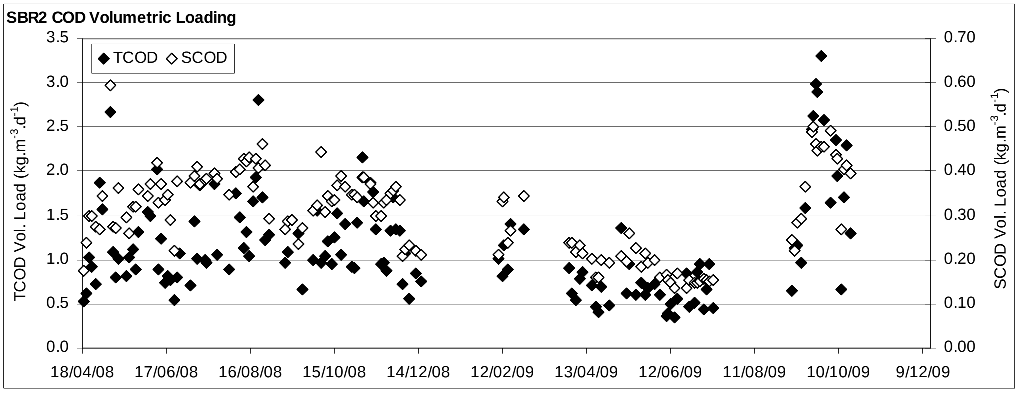


Figure 3.12: SBR 1 nutrient and COD loadings (volumetric and mass).







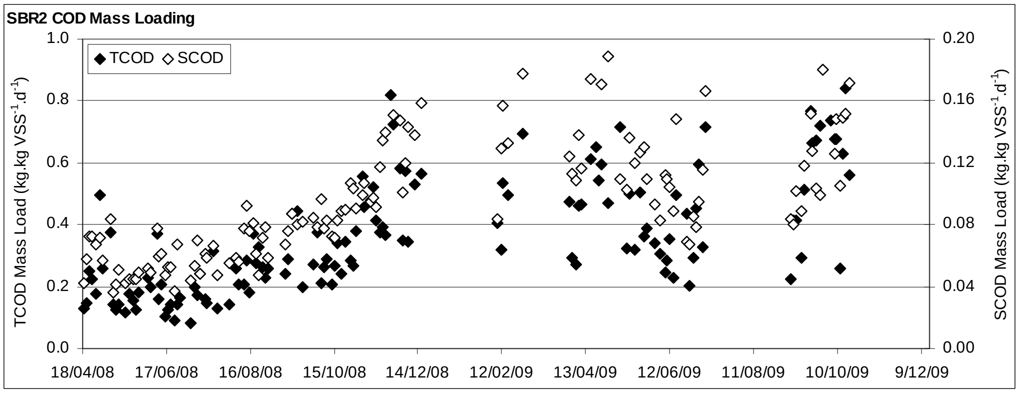


Figure 3.13: SBR 2 nutrient and COD loadings (volumetric and mass).

3.3 Experimental Phases of Operation

The pilot-plant operation can be broadly classified into a number of experimental phases or observation periods:

- Section 4.3.1 – Reduced settle time selective pressure
- Section 4.3.2 – Cycle and feeding regime manipulation
- Section 4.3.3 – Shock loading
- Section 4.3.4 – Prefermenter optimisation
- Section 4.3.5 – Increased hydraulic loading
- Section 4.3.6 – Increased Feed Event Loading

The attempts to achieve granulation and maintain the granules in the system were performed while also trying to maintain reasonably good N and P removal. At no stage was granulation attempted without maintaining N and P removal. This was due to the inhibitory affects high ammonia has on the nutrient removal process, as observed in laboratory-scale reactors.

3.3.1 Reduced Settle Time Selective Pressure (Apr.-Sep. ’08)

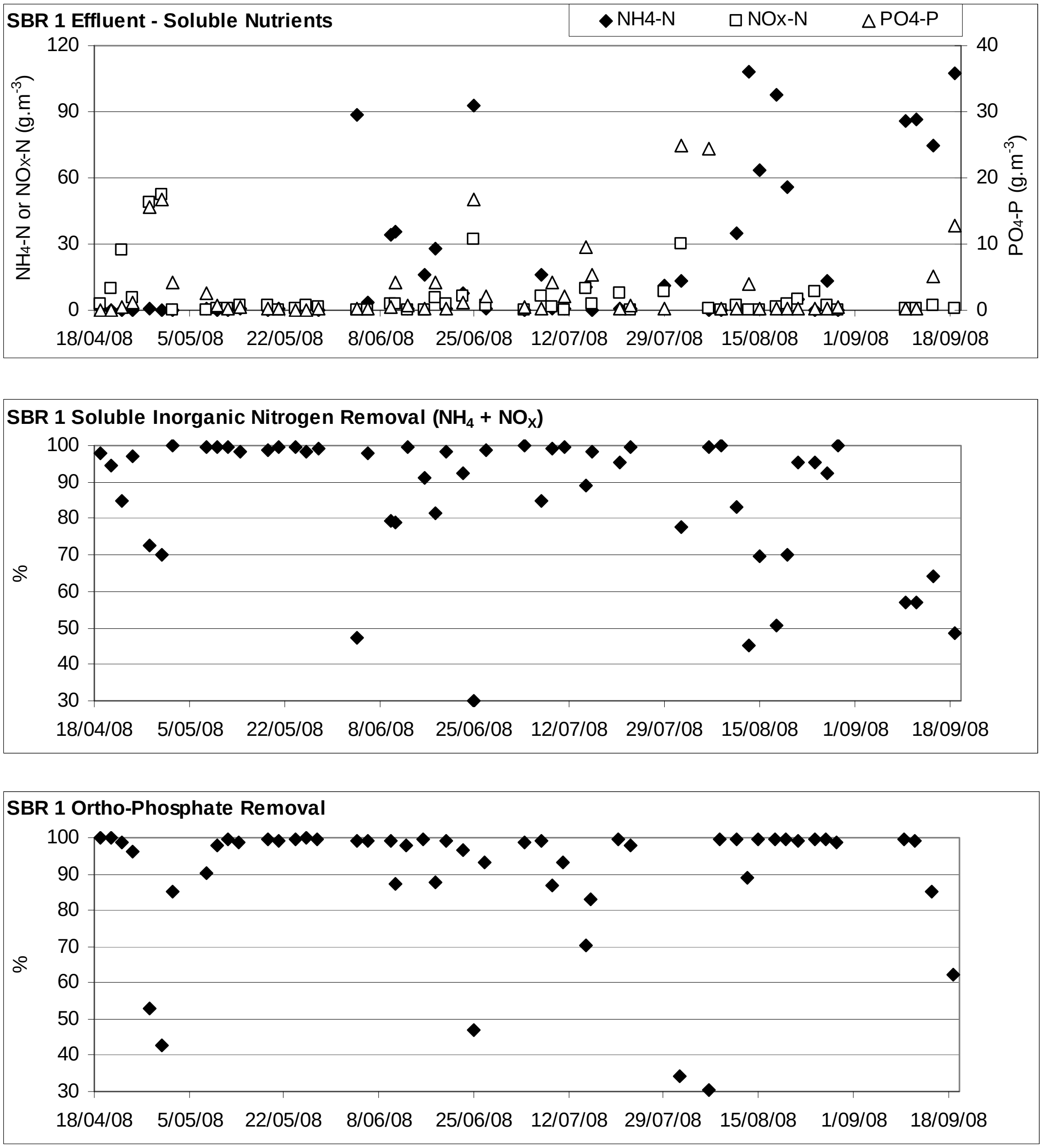
3.3.1.1 SBR 1

Once the base hydraulic loading rate of 0.57 $m^3.m^{-3}.d^{-1}$ was achieved (as described in Section 3.1) investigations into a reduced settling time as a selection pressure for granulation were undertaken. For SBR 1, the settling time was gradually reduced from 30 min on 8/5/08 down to 5 min on the 7/6/08 (see Appendix 2 for cycle time changes). The cycle was maintained at 6hr with the extra time from settle reduction added to the decant time (this resulted in the SBR sitting idle for a period of time following decanting).

The pilot-plant was maintained with a 5min settle without any major changes until 26th August, 2008. During this period, good NH_4-N, NO_X-N and PO_4-P removal continued as shown in Figure 3.14**Error! Reference source not found.**. While there were periods with elevated nutrient concentrations, these were all related to operational issues and not loss of activity.

The good nutrient removal continued to occur despite continued washout of sludge in the effluent. At this time, sludge wastage had ceased and so sludge turnover was due solely to washout in the effluent. Figure 3.15 shows the resulting SRT and suspended solids concentration in SBR 1 due to the washout of sludge. During this period the aerobic SRT was typical <3 days and yet the system was able to maintain excellent soluble nitrogen removal. This highlights a shortcoming with the typical SRT measurement, which does not take into account the continued addition of solids with the feed stream, which for this project was a significant load. Since most of the influent solids were small particles with limited settleability, it is expected that a substantial fraction of the effluent TSS is contributed by these incoming solids, hence the SRT does not really reflect accurately the true retention time of the biomass in the system.

Figure 3.16 shows the particle size analysis for SBR 1 suspended solids and effluent solids. Initially there was a particle size increase for the sludge, particularly for the 90%ile. However, this soon changed to a stable measurement. From 11/8/08-20/8/08 a particle size increase for the sludge was observed but then returned to prior measured values. The method of particle size loss appears to be washout of the sludge with the effluent and not solublisation of the particles, as indicated by the particle size measurements of the effluent solids.


SBR 1 Effluent - Soluble Nutrients

SBR 1 Soluble Inorganic Nitrogen Removal (NH_4 + NO_X)

SBR 1 Ortho-Phosphate Removal

Figure 3.14: Nutrient removal in SBR 1 (period 18/4/08 – 20/9/08).

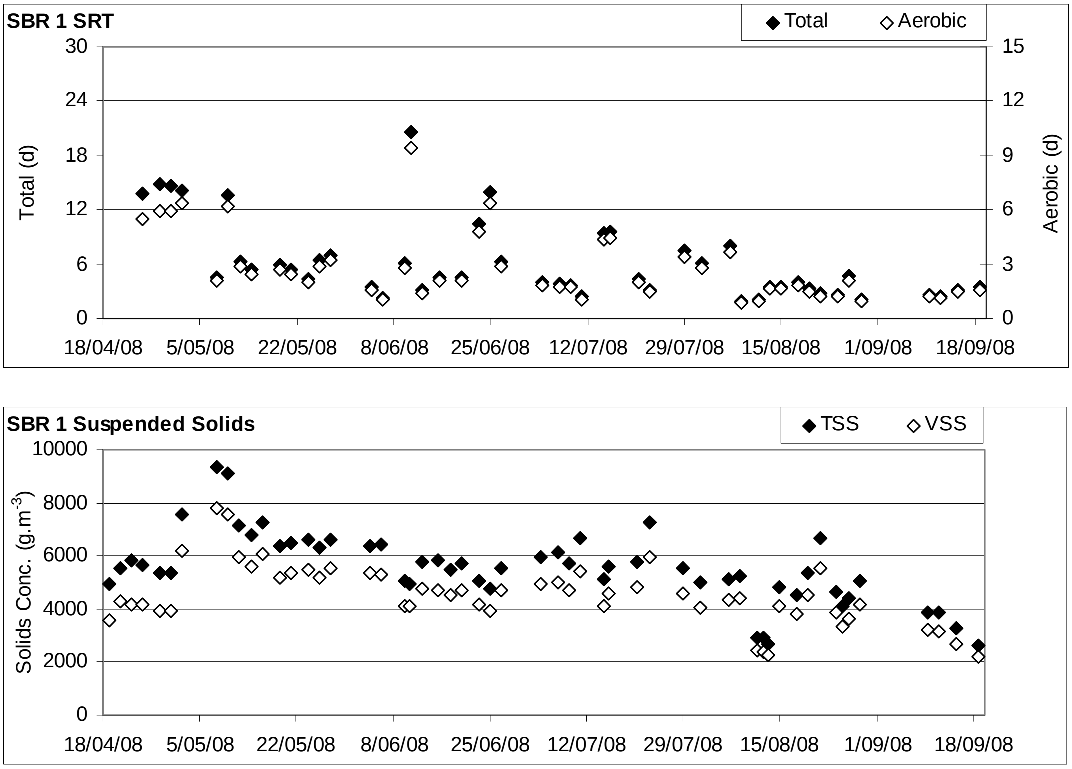


Figure 3.15: SBR 1 solids retention time and suspended solids concentration (period 18/4/08 – 20/9/08).

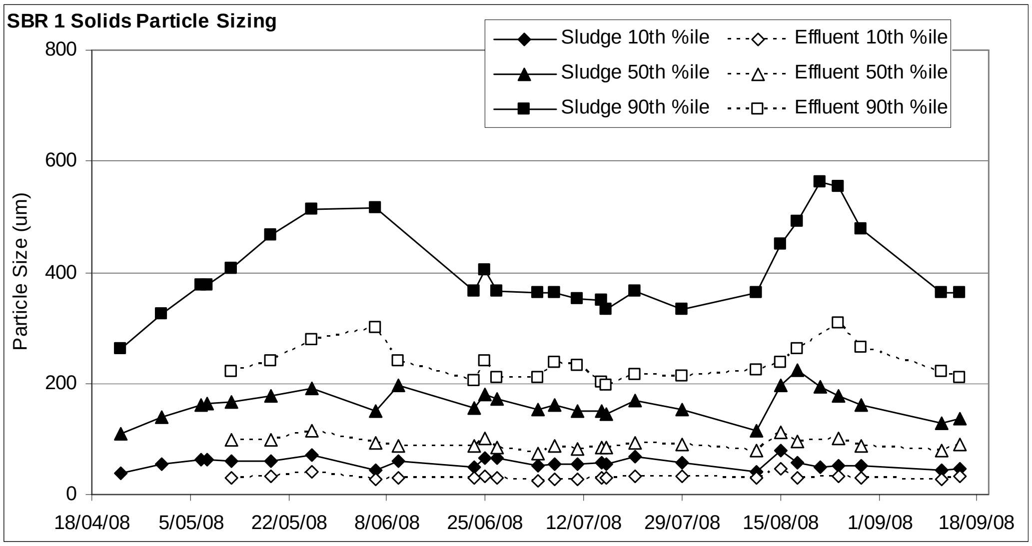


Figure 3.16: SBR 1 particle size analysis for suspended solids and effluent solids (period 18/4/08 – 20/9/08).

The SBR suspended solids concentration reduced throughout this study period at a very slow rate. This indicated that although there was significant loss of biomass in the effluent, the biomass was continually replenished. This is completely different to observations with lab-scale rigs where the settle reduction results in a significant decrease of suspended solids. The major difference between the systems is the method of decanting. Lab-scale reactors are typically cylinders with a high aspect ratio and the decant port is located at a lower level than the top water level. In the pilot-plant, the aspect ratio is low and the decant port based on a floating system which alters as the surface level decreases. As well, the decant of lab-scale rigs is typically a fast process (within minutes) as compared to the much slower pumping process required for larger scale systems. Thus, it appeared the selective pressure of a reduced settle in the system was not sufficient to encourage granulation. With this in mind, the decant setup for SBR 1 was altered on 26/8/08. The new system involved removal of the float and connecting the flexible hose to a 2 m length of 25 mm ID pipe with 4 x 15 mm diameter holes located equidistant along its length. The pipe was fixed by hanging it from the pilot-plant upper frame and initially placed at 150 mm below bottom water level (BWL). This was later reduced to 230mm below BWL (27/8/08). This decant apparatus change had no affect on the particle size but did appear to result in a more rapid decrease in sludge concentration (Figure 3.15).

It was concluded that settle time reduction alone, even with a submerged multiple point decant, would not cause granulation.

3.3.1.2 SBR 2

Prior to reducing the settling time for SBR 2, the load was first increased to observe if this offered any benefits. Once the base hydraulic loading rate of 0.57 $m^3.m^{-3}.d^{-1}$ was achieved (as described in Section 3.1) the hydraulic load was increased from 0.57 $m^3.m^{-3}.d^{-1}$ on 8/5/08 to 0.84 $m^3.m^{-3}.d^{-1}$ on 27/5/08 (a 47% increase in load compared to SBR 1). The SBR operation was continued with this loading and a 3 0min settle time until the 20/8/08.

Nutrient removal throughout this period remained good (Figure 3.17**Error! Reference source not found.**) except for occasional spikes related to operational issues (as for SBR 1).

The SRT (Figure 3.18) was more variable due to loss of solids in the effluent. These solids exited in the decant towards the end of the pumping period due to the decant suction port entering the settled sludge blanket (this reactor continued operation with a floating decant). Despite the loss of sludge in the effluent, the reactor still maintained a high suspended solids concentration.

There was a particle size increase of the sludge towards the end of June (Figure 3.19) but this returned to previous levels shortly after. Note that this particle size increase was not observed at this time for SBR 1.

Once it was determined the additional hydraulic load would not result in granulation, the settling time was gradually reduced from 30 min on 20/8/08 to 5 min on 30/8/08 (see Appendix 2 for cycle time changes). This settle reduction was performed at a considerably faster rate than was done for SBR 1. Continued operation with a 5min settle period showed no increases for the sludge particle size and it was concluded that a low settle time, even with a higher loading, would not cause granulation.

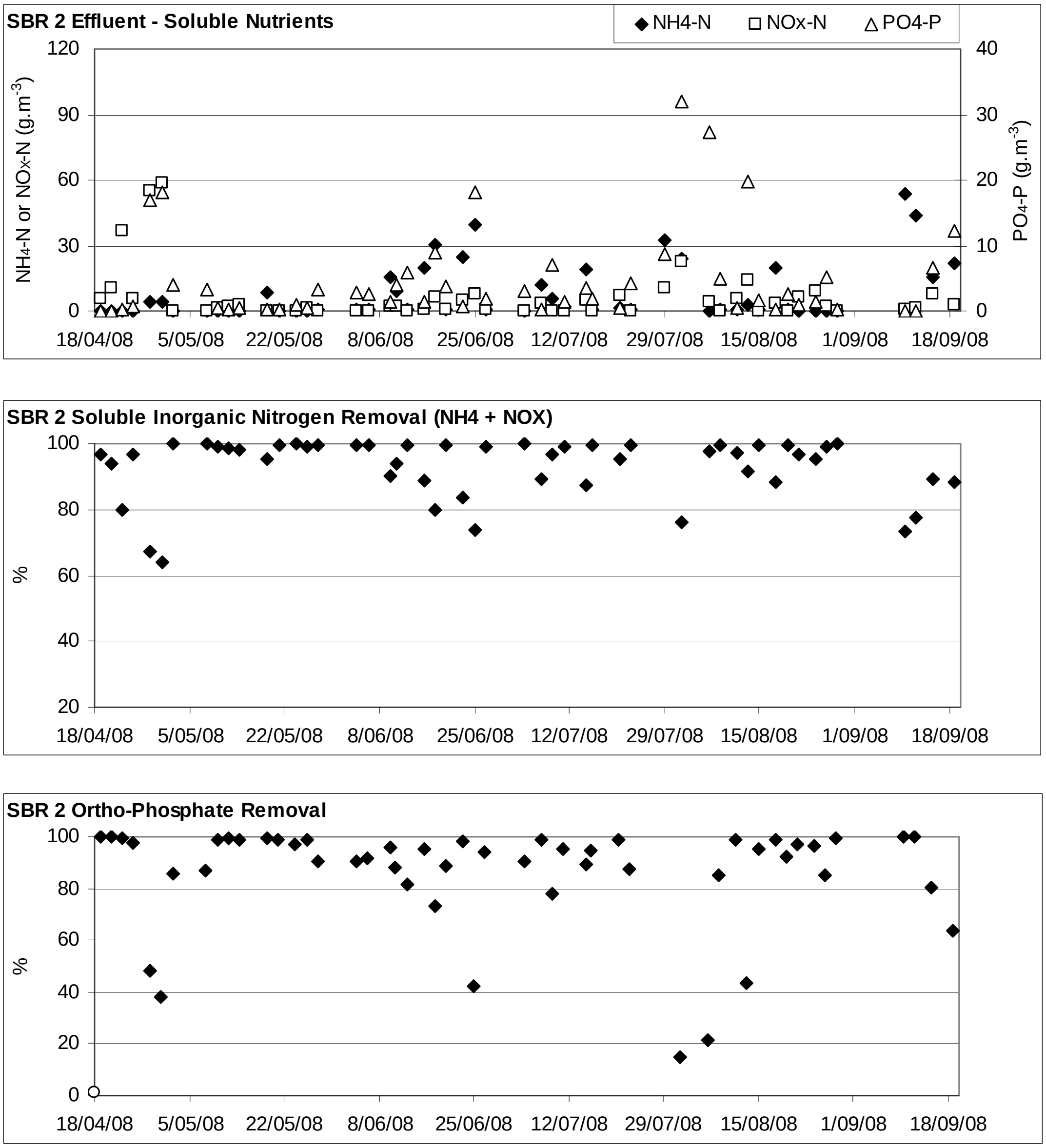


Figure 3.17: Nutrient removal in SBR 2 (period 18/4/08 – 20/9/08).

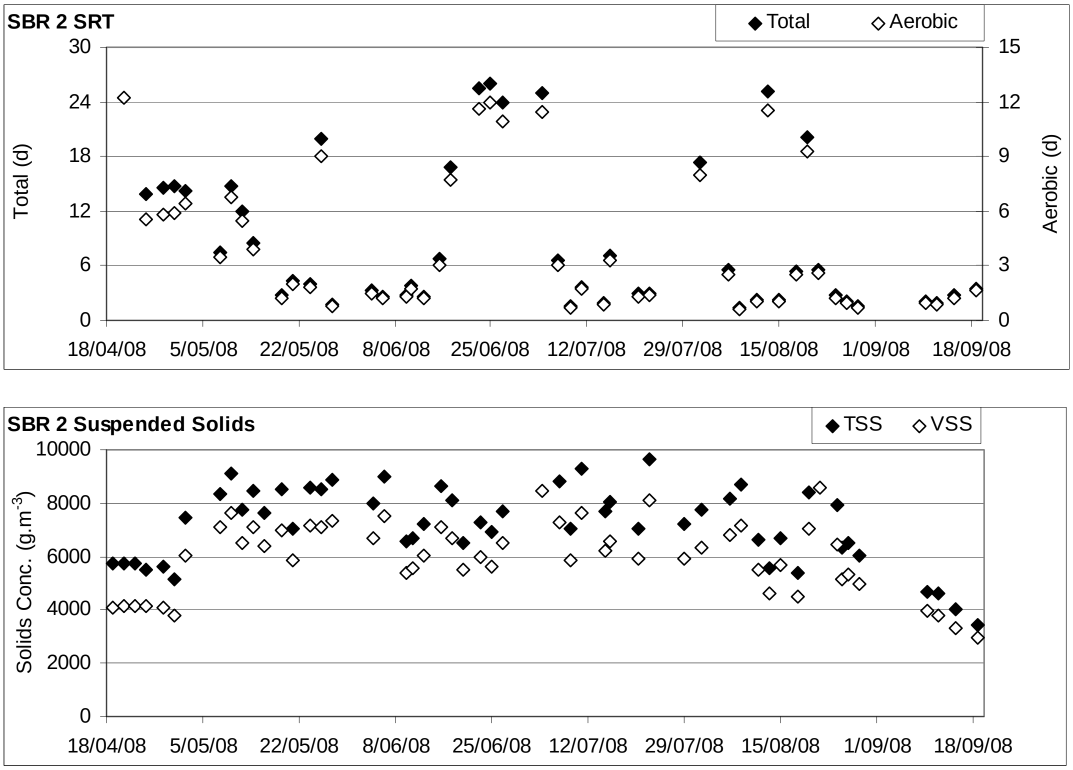


Figure 3.18: SBR 2 solids retention time and mixed liquor suspended solids concentration (period 18/4/08 – 20/9/08).

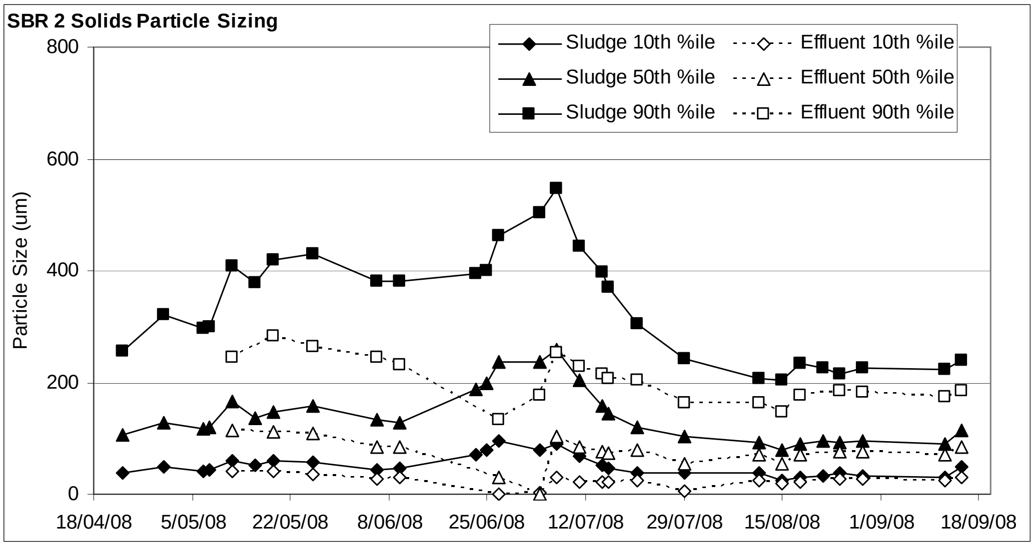


Figure 3.19: SBR 2 particle size analysis for suspended solids and effluent solids (period 18/4/08 – 20/9/08).

3.3.2 Cycle and Feeding Regime Manipulation (Sep.-Dec. ’08)

Once it was found that a reduced settle time alone would not cause granulation in the system, major changes to the cycle timings and feed supply were undertaken (see Appendix 2 for cycle time changes). The major changes were:

- An increase in the feeding times while maintaining the same feed rate – this resulted in an additional time period after feeding where nothing happened. It was hoped further hydrolysis and fermentation of particulates from the prefermenter stream would occur within the SBRs, increasing the available VFA and decreasing the particulate COD. Implemented 20/9/08
- Staggered feeding with feed 1 providing 50% of the total cycle load, feed 2 30% and feed 3 20%. This is the same feed strategy used in the previous study and it was hoped the higher shock loading from the first feed would help to stimulate granulation. When this was implemented, the feed preparations for the SBRs were separated so each feed batch for each SBR was prepared fresh for that SBR alone. Implemented on 8/10/08.

Following these changes, granulation was observed in SBR 1 and to a lesser extent in SBR 2 (Figure 3.20). The particle size increase for SBR 1 occurred prior to the staggered feed implementation so it can be concluded this played no role in stimulating granulation. The sludge median particle size reached a maximum of 400 µm for SBR 1 before rapidly dropping to previously measured values.

Figure 3.21 shows stereomicroscope images of SBR 1 sludge on 30/10/08 (peak of particle size analysis). The sludge was clearly dominated by granules. This was in direct contrast to the sludge from SBR 2 at the same time (Figure 3.22). While some granules can be observed in SBR 2 sludge, it was largely dominated by floccular sludge.

The sludge concentration of SBR 1 began to increase during the granulating period (Figure 3.23). This indicates the granules were grown during the process rather than selectively retained over the floccular sludge during the decant washout.

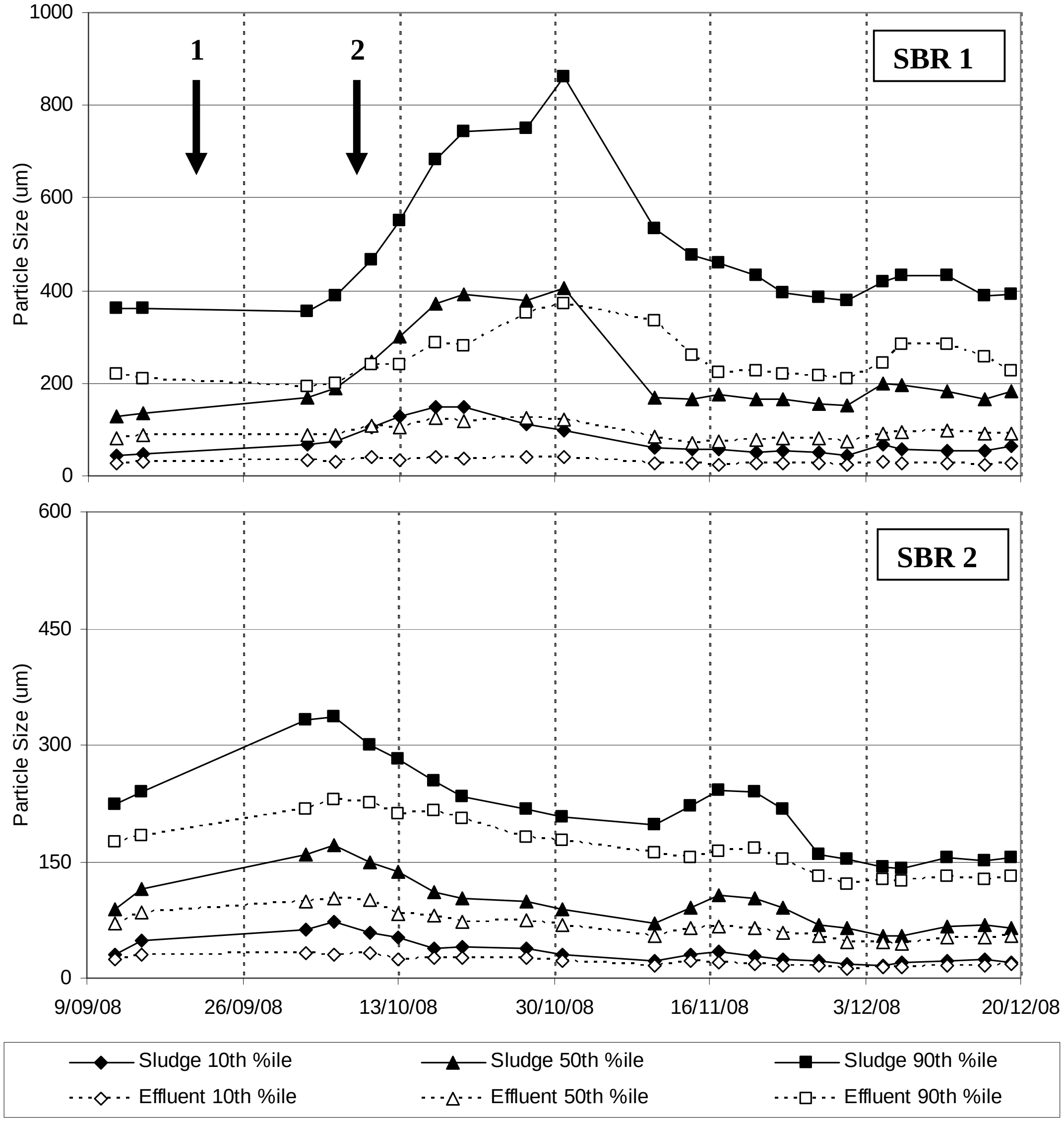


Figure 3.20: SBR 1 and SBR 2 particle size analysis, 9/9/08-19/12/08. Arrow 1 indicates cycle changes; arrow 2 indicates implementation of staggered feed.

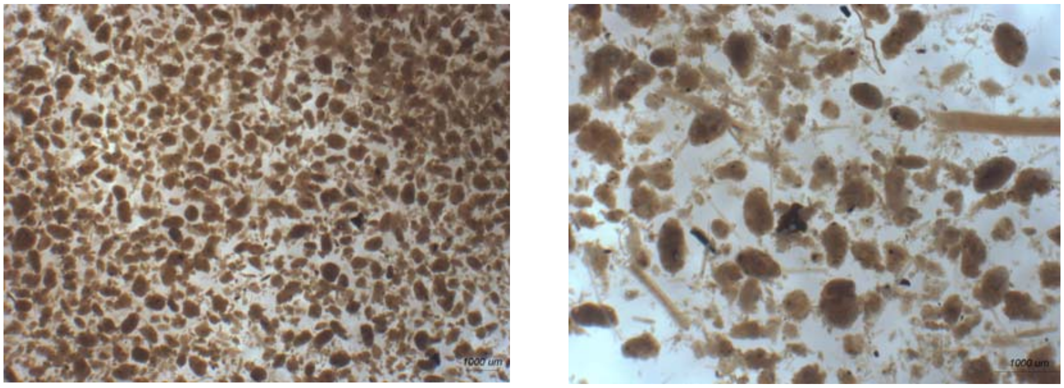


Figure 3.21: Stereomicroscope images of SBR 1 sludge on 30/10/08.

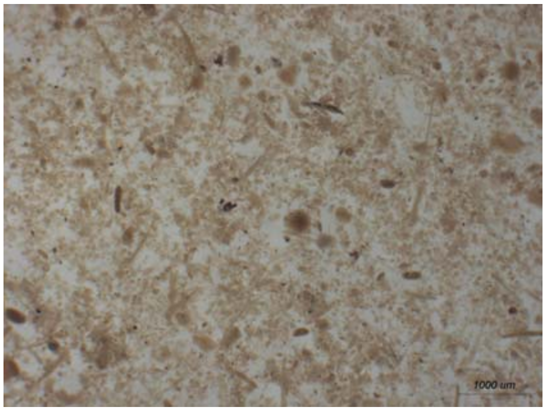


Figure 3.22: Stereomicroscope image of SBR 2 sludge on 30/10/08.

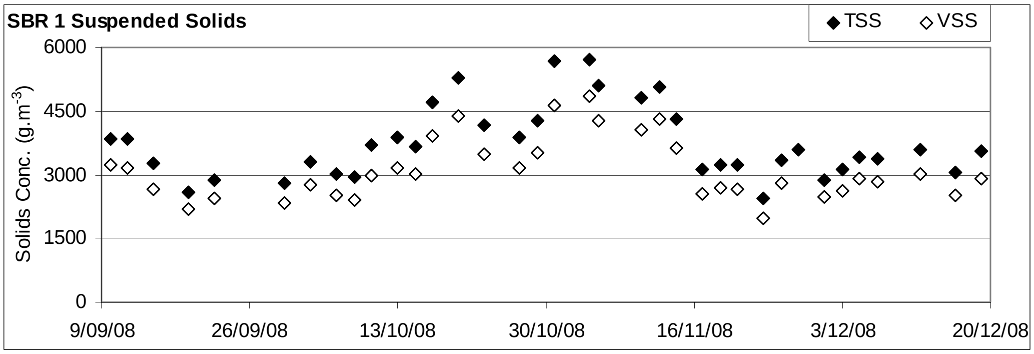


Figure 3.23: SBR 1 suspended solids concentration (period 9/9/08-19/12/08).

The cause of granule loss from SBR 1 was likely due to a large increase in rapidly degradable solids from the prefermenter (see Figure 3.9). This increased solids loading appears to have resulted in excess floccular heterotrophic growth during the aerobic periods, which entrapped the granules during settling and they were subsequently washed out along with the floccular material. This is indicated by the delayed decrease in effluent solids particle size (Figure 3.20).

During this phase of operation, the major differences between the two SBRs was the higher loading in SBR 2 (0.84 $m^3.m^{-3}.d^{-1}$ compared to 0.57 $m^3.m^{-3}.d^{-1}$ for SBR 1) and the submerged multiple point decant in SBR 1 compared to the floating one-point decant in SBR 2. At the time, it was thought the submerged decant port was critical to the extent of granule development in SBR 1, since SBR 2, which did not have this form of decant apparatus, did not develop the granules to the same extent. The same decant apparatus was incorporated into SBR 2 on 11/11/08 and both SBRs operated in the same fashion until the end of the year. However, no further granulation was subsequently observed.

3.3.3 Shock Loading (Feb.-May '09)

Prior to the granule development observed in October 2008, both SBRs were operated with a lower % volume of prefermenter feed. Initially the prefermenter feed % was 20-22.5% and this was reduced to 15% and finally 10% in the 2 weeks prior to the SBR 1 granulation period. This was then returned to a 15% load for 3 days prior to the plant shutting down for 5 days due to operational problems. Upon restarting the plant, granulation was observed in SBR 1. The reduction in carbon entering the SBRs resulted in reduced sludge concentrations within the reactors (approx. 2.8g/L in SBR 1 and 4.3g/L in SBR 2).

It was thought the rapidly increasing prefermenter loading, coupled with the reduced sludge concentration (and thus higher mass loading) may have been responsible for the initiation of SBR 1 granulation. Following the Christmas/January shutdown of the abattoir (total of 6 weeks), the pilot-plant was restarted with new cycle times (see Appendix 2) which varied the length of aeration proportionally with the 50/30/20% feeding regime. The SBR 2 hydraulic loading was also changed back to the base loading of 0.57 $m^3.m^{-3}.d^{-1}$ (same as for SBR 1). Once good nutrient removal was observed for both SBRs a shock loading experiment was performed to try to replicate the higher mass loadings. This was achieved by manually wasting mixed liquor from the SBRs during an aerobic period (SBR 1 was reduced to 2600 $g.m^{-3}$ and SBR 2 to 2200 $g.m^{-3}$ TSS). SBR 2 was then operated under the same cycle conditions as used previously but the feed for SBR 1 was alternated continuously between one day with a feed of 10% prefermenter volume and the following day of 20% prefermenter volume. This was done to determine if a shock increase in VFA loading assists in granule development.

After several weeks of operation it was observed the shock loading described had no effect on the suspended solids particle size (Figure 3.24). It simply resulted in a slightly higher effluent nutrient concentration for SBR 1. During this testing period, the prefermenter effluent COD was high and so it is not possible to determine whether the experiment failed or whether the high non-VFA COD exiting the prefermenter was responsible, preventing the accumulation of granules. The high prefermenter effluent COD appeared to be caused by high prefermenter temperatures (37-39ºC) solubilising fats in the tank and reducing the settleability of the prefermenter sludge.

Subsequently the plant was shutdown in March while external temperatures decreased. Upon restart in April, the prefermenter temperature remained below 35ºC and the effluent COD was also lower.

In April the conditions leading up to the previous granule formation were replicated, except for the 5 day shutdown period. This involved operating the SBRs with a 15% prefermented liquor feed, followed by a short period (several days) of 10% mix before returning to a 15% mix. Again there was no effect on the sludge particle size (Figure 3.24). It was concluded that there was another factor which was required to initiate granulation, possibly the prefermenter VFA and non-VFA COD concentrations. This is discussed further in Section 3.3.4.

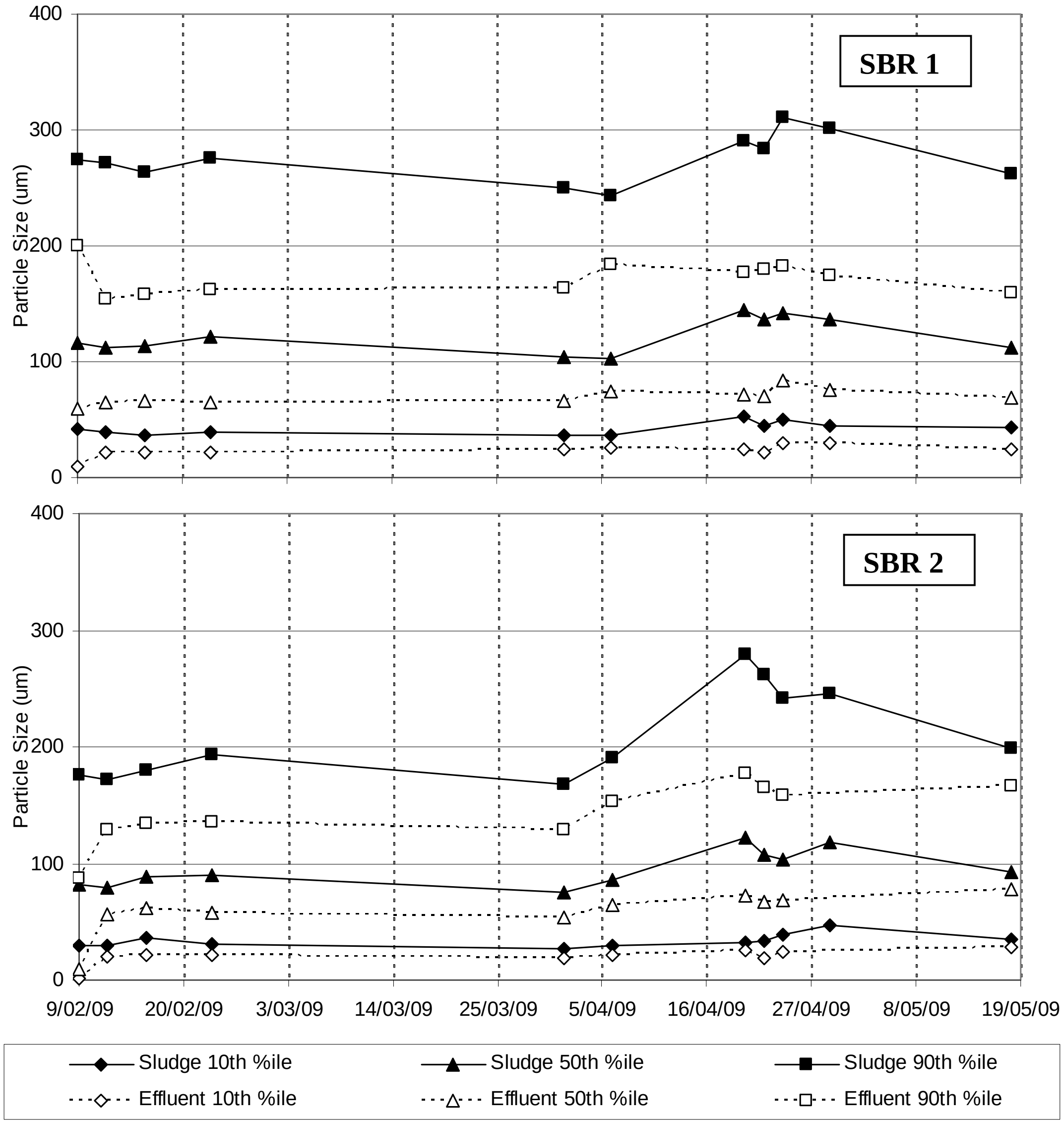


Figure 3.24: SBR 1 and SBR 2 solids particle size analysis (period 9/2/09 - 19/5/09).

3.3.4 Prefermenter Optimisation (May-Dec. '09)

By the end of 2008, it became evident that the prefermenter operation was critical to the development of granules in this system. Further examination of the data revealed that during the granulation in SBR 1 in October 2008, the prefermenter VFA concentration was higher than normal and the non-VFA COD (mainly in particulate form) was lower than normal. With this in mind attempts were made to optimize the prefermenter to reduce the non-VFA COD (mainly in particulate form) exiting the prefermenter.

The prefermenter was constructed using a simple rainwater tank without baffling. Shortly after startup in 2008, a thick fat layer developed on the top of the tank and remained throughout the year. This same fat layer was observed in the previous project as well.

Optimisation of the prefermenter included investigating:

- various depths (vertical) and positioning (horizontal) of feed delivery
- different HRTs
- different mixing regimes (frequent vs infrequent)
- incorporating an Induced Air Flotation unit
- extended settling

In May and June the feed delivery was altered in height (bottom feeding and mid-level feeding) and position (further away from the transfer pump to the mixing tank) with little affect on effluent solids or VFA concentration. After changing the inlet to trickle in at the surface (1/6/09) there was a significant reduction in effluent solids while maintaining typical VFA concentrations (Figure 3.25). However, this resulted in major accumulation of fat on the surface which eventually split the roof of the tank. Subsequently, the tank was emptied and the prefermenter restarted on 22/6/09.

After restart, it was found the fat layer only redeveloped after a weekend period when no feeding occurs and the temperature typically drops. While there was no fat layer, sludge in the prefermenter could be seen to move, remaining suspended even after a 50 min non-mixing period.

In July and August 2009, the plant was plagued by many operational issues, resulting in frequent shutdown of the plant. No data was collected during this period.

In September 2009, an Induced Air Flotation (IAF) unit was trialed on the prefermenter effluent stream. IAF works along the same principles as Dissolved Air Flotation, using fine bubbles to trap solids and fats and float them to the surface. It was found the IAF did remove solids but the rate of removal was considerably lower than expected and was also dependent upon the starting solids concentration. At a high TSS concentration (4400 $g.m^{-3}$) a removal rate of 103 g $TSS.m^{-3}.min^{-1}$ was observed compared to 3 g $TSS.m^{-3}.min^{-1}$ for a low initial TSS concentration (540 g $TSS.m^{-3}$). An excessive amount of foam was also generated, possibly due to cleaning products used by the abattoir passing into the "red stream".

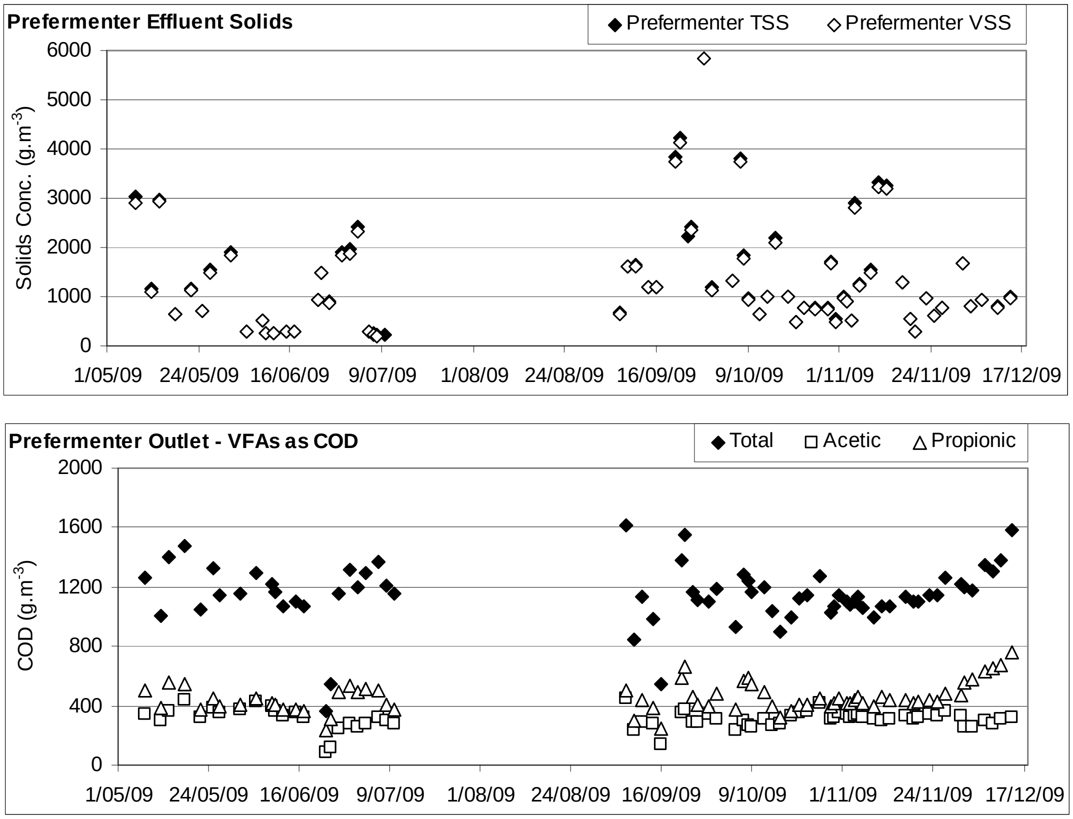


Figure 3.25: Effluent TSS and CODVFA from prefermenter during optimisation period.

From mid-September 2009 to the end of the project, changes to the mixing regime were performed which included changing the length of the mixing event as well as the frequency of mixing. However, it was impossible to correlate any of the changes with changes to the prefermenter performance. This was likely due to the dynamic environment. Frequent mid-week shutdowns of the abattoir added to this dynamic nature.

In September and October 2009, investigations in varying HRTs was undertaken to optimize for VFA production rather than effluent suspended solids reduction. The data (Table 3.2) suggests the optimum HRT for VFA generation is between 1-3 days. However, again the study was influenced by the highly dynamic wastewater composition as well as time limitations.

Table 3.2: Effect of HRT on VFA concentration.

HRT (days)	Average VFA Concentration ($g.m^{-3}$)	Length of Study (days)	No. of Measurements
0.66d	603	9	4
1d	816	29	12
3d	771	28	14

From mid-November until the end of the project, investigations into extended settling times were undertaken. It had been observed throughout the project that the prefermenter effluent suspended solids were typically low following a period of extended non-feeding. These periods were typically weekends but also included weekdays when the abattoir was shut down. It is likely that the reason for a reduced effluent solids concentration is the solidification of entrained fats (which float to the surface) due to cooling of the liquor. The reduced soluble fat then allows for better settling of the prefermenter sludge during the non-mixed periods just prior to feed preparation.

The extended settling tests involved stopping all mixing and feeding into the prefermenter for 4-5 hours and then pumping the required prefermenter volume for 2 or 3 cycles into a separate tank. These transfers were done every 12 hours. The prefermented liquor required for feed preparation was then taken from the separate tank.

The effectiveness of the extended settling approach was highly variable, at times producing a liquor with low solids and at other times one with very high solids. The lack of success is likely due to insufficient time for cooling of the liquor necessary for the solidification of fats.

Towards the end of the project, there was an increasing VFA concentration observed. This appears directly related to the prefermenter temperature with a rising temperature resulting in a rising VFA concentration (as discussed in Section 3.2.2).

3.3.5 Increased Hydraulic Loading (Sept.-Oct. ‘09)

To determine if an increased hydraulic loading would help to stimulate granulation, the HRT of both SBRs were reduced from 42 hr on 4/9/09 (hydraulic load of 0.57 $m^3.m^{-3}.d^{-1}$) to 18 hr on 21/9/09 (hydraulic load of 1.33 $m^3.m^{-3}.d^{-1}$). This was done by increasing the feed volumes per feed event (while maintaining the 50/30/20% feeding regime), decreasing the bottom water level in the SBRs (maintaining a top water level of 6 m^3) and also reducing the cycle times to result in a total cycle time of 4.8 hr instead of the previously used 6 hr (see Appendix 2).

Figure 3.26 shows the suspended solids and effluent particle size measurements. SBR 1 showed a small particle size increase in the later part of September before decreasing to previously observed values. SBR 2 showed an even lower increase prior to returning to previously observed values. It appears these particle size changes were not related to granulation but rather carryover of bulk liquor VFA (i.e. VFA which has not been stored intracellularly) into the aerobic phases during load increases. Such carryover would allow for rapid growth of heterotrophic bacteria and a subsequent increase in floc size. As the population of bacteria which can store VFA intracellularly (PAO and GAO) increased in number due to the higher loading, the amount of VFA carried over to the aerobic phases would decrease, slowing the floc size increase. The particle size decrease then occurred due to the continued washout of flocs during decant. Note that no VFA measurements were performed on samples collected at the start of the aerobic periods. Thus, while this explanation is plausible, it is still speculative without this supporting data.

The difference in the extent of floc size increase/decrease appears to be related to different population levels of bacteria which can accumulate VFA intracellularly within each SBR. Figure 3.27 shows that SBR 2 appeared better in handling the rapid increase in ortho-phosphate and VFA loading as compared to SBR 1, thereby reducing the VFA carryover into the aerobic phases.

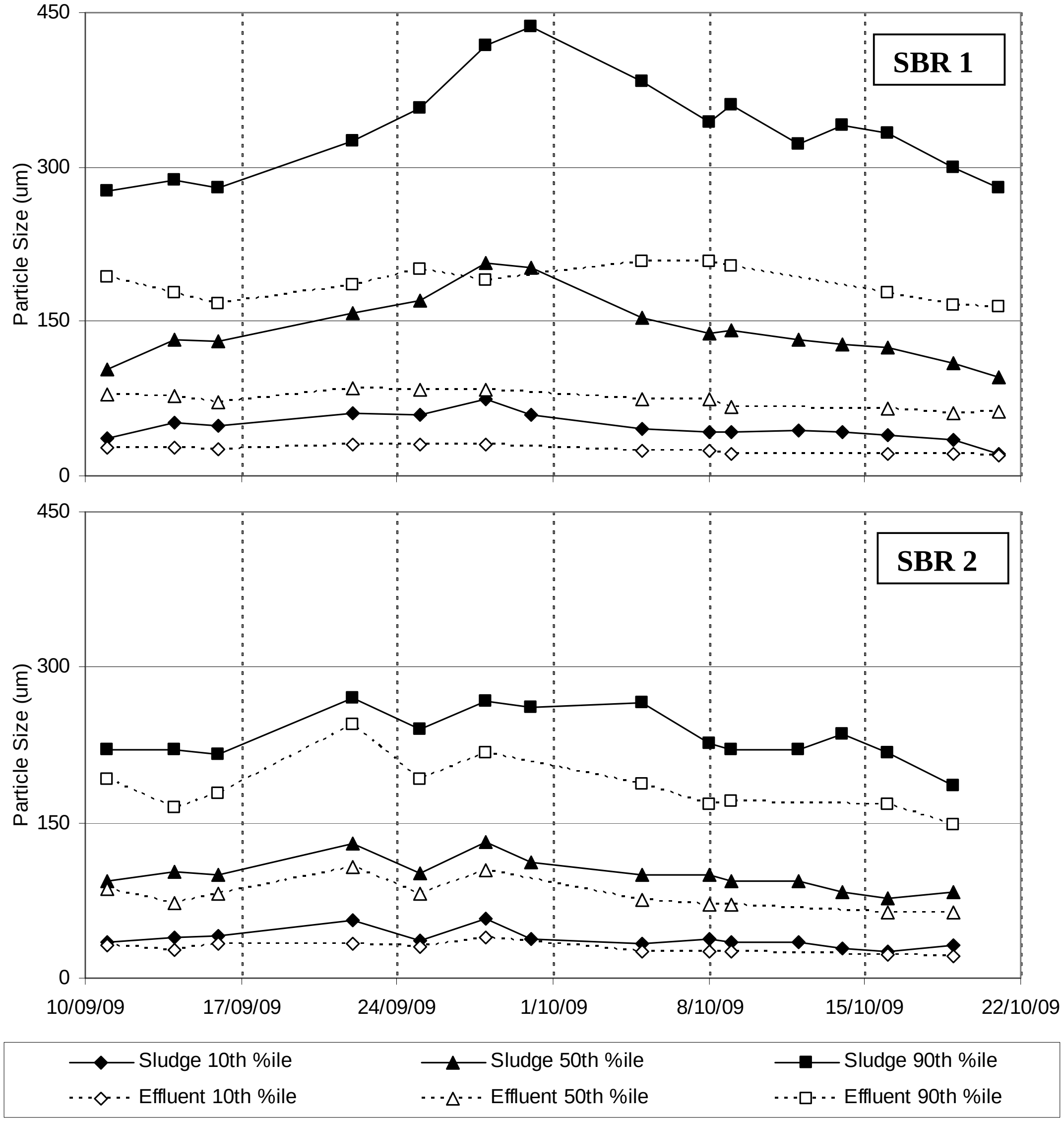


Figure 3.26: SBR 1 and 2 particle size analysis during hydraulic load increase (period 11/9/09 – 21/10/09).

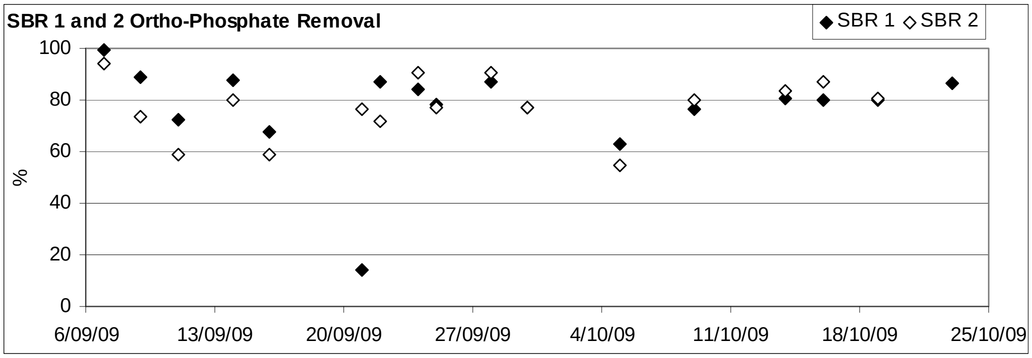


Figure 3.27: SBR 1 and 2 ortho-phosphate removal during hydraulic load increase (period 11/9/09 – 21/10/09).

SBR 2 was shutdown on 19/10/09 to allow for better manipulation of non-mixed times in the prefermenter. SBR 1 continued to operate to the end of the project with the higher loading at 1.33 $m^3.m^{-3}.d^{-1}$ (18hr HRT). Towards the end of 2009, the typical seasonal anaerobic pond effluent temperature increase was observed, particularly during November and December (Figure 3.6). However, the increased hydraulic load resulted in SBR 1 operating at relatively high temperatures in terms of nutrient removal.

Figure 3.28 indicates the ortho-phosphate removal rate was inhibited by temperatures > 36ºC whereas the nitrogen removal rate was inhibited by temperatures > 38ºC. As discussed in Section 3.2.1, the black pipe used for transferring the anaerobic pond liquor to the pilot-plant artificially elevated the water temperature by 2-3ºC on sunny days. However, even if this is taken into account, it is clear that there would still be days in a sub-tropical region when the SBR temperature would adversely affect the nutrient removal process. Note that SBR 1 was shutdown on 19/12/09 (project end) and so only limited data could be collected to determine the effects of the elevated temperature.

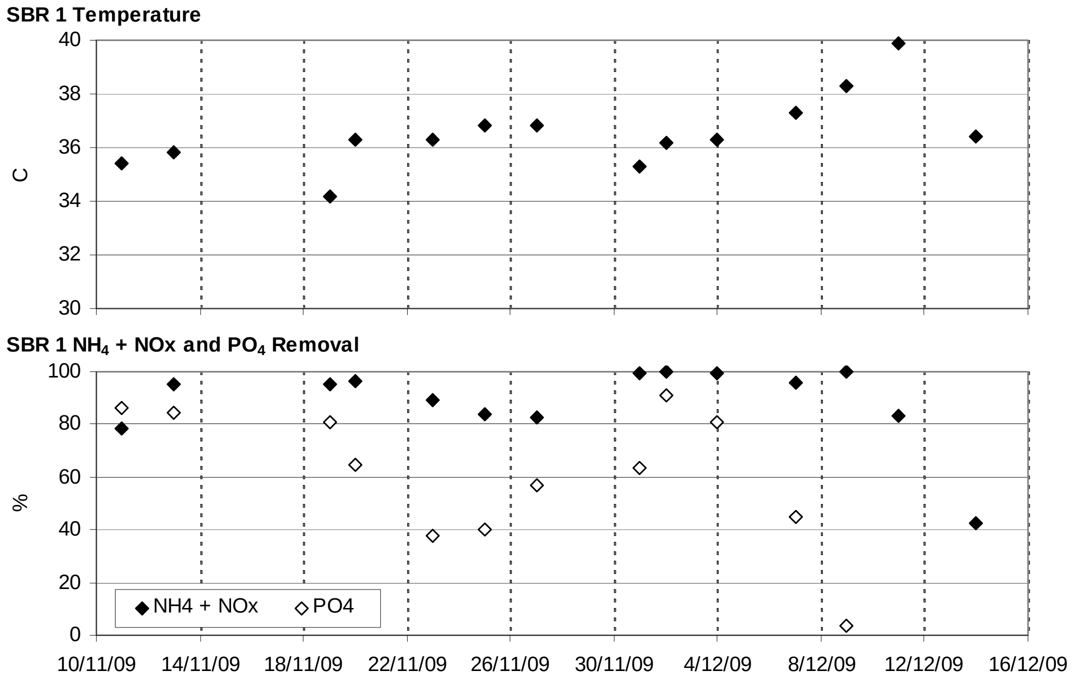


Figure 3.28: Effect of temperature on ammonia + NO_X and ortho-phosphate removal in SBR 1.

3.3.6 Increased Feed Event Loading (Oct. – Nov. ’09)

On 27/10/09, the cycle for SBR 1 was dramatically altered to only one feed, anoxic and aerobic period instead of the 3-staged feed (see Appendix 2 for detailed cycle times). The same hydraulic loading was retained. Due to the limited size of the feed mixing tank, the feed preparation and delivery was altered so that the required prefermented liquor volume was first added to the mixing tank and then the tank filled to 0.8 m^3 with anaerobic pond effluent, thus creating a feed mix of 30% prefermented liquor. This feed batch was fed to the SBR and when the mixing tank volume had decreased to 0.05 m^3 (i.e. 0.75 m^3 fed), more anaerobic pond effluent was added to the mixing tank while the SBR continued to be fed. The intermittent addition of pond effluent to the mixing tank continued until the total required feed volume (as measured by the SBR pressure sensor) had been fed to the SBR. Thus, while the same overall feed fractions and total cycle loading rates were the same, the individual feed event loading rates were significantly higher.

Immediately following these changes, there was a very rapid suspended solids particle size increase (Figure 3.29) followed by a reduction. This particle size increase again appears to have been due to carryover of VFA into the aerobic period as discussed previously in Section 3.3.5. Once the bacterial population which store VFA intracellularly had increased in numbers, as indicated by the increase in ortho-phosphate removal (Figure 3.29), VFA carryover ceased and the particle size decreased due to sludge turnover from the decant washout.

Microscopic examination of the sludge (Figure 3.30) showed that while there were some granule-like particles present, the majority of the sludge was formed from loose, large flocs.

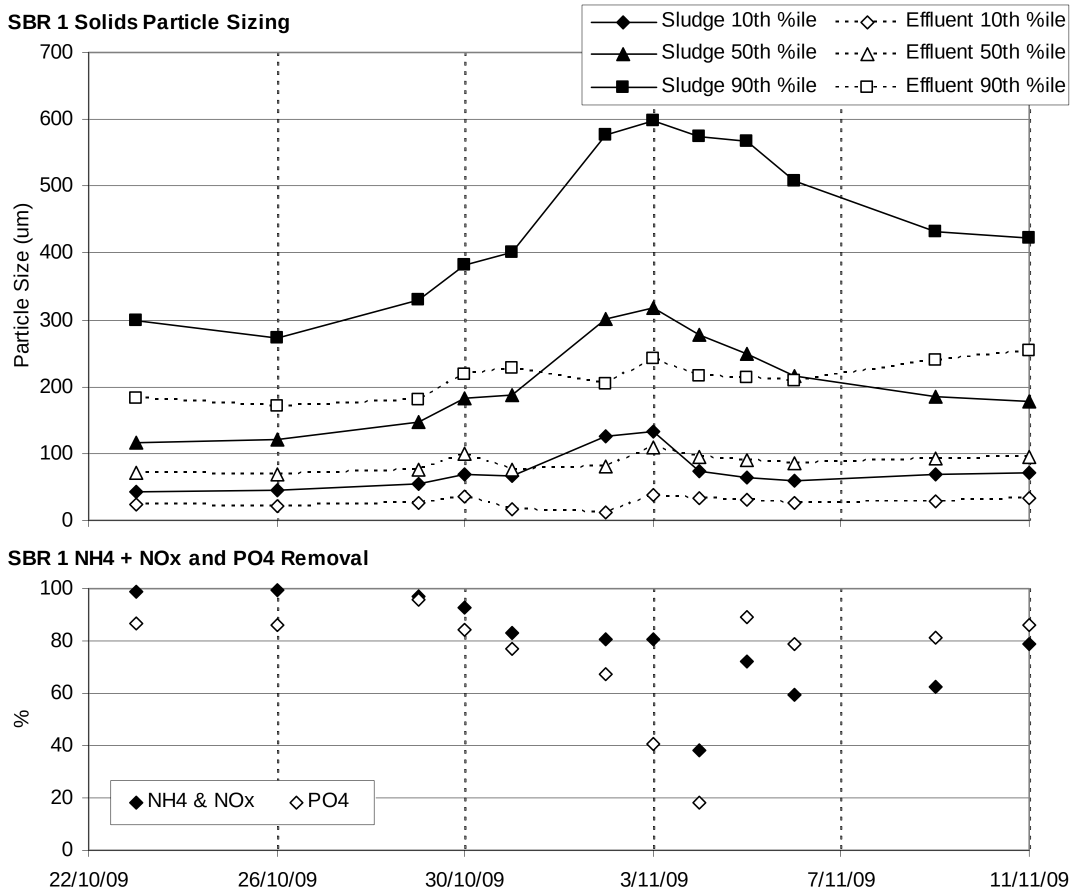


Figure 3.29: Suspended solids and effluent solids particle size and nutrient removal for increase feed event loading trial.

Figure 3.30: Stereomicroscope image of SBR 1 sludge on 3/11/09.

3.4 Discussion

3.4.1 Identification of Granulation Driving Factors

Granulation has been achieved at laboratory scale for a number of different systems, including removal of carbon, nitrogen or phosphorous separately and carbon, nitrogen and phosphorous removal combined. Driving factors for each system are likely different due to the bacteria present. In this system, there also appear to be number of driving factors and identifying these factors was difficult due to the dynamic nature of the site.

Figure 3.31 shows graphs for SBR 1 with identified periods of granulation (or the beginning of granulation) followed by loss of forming granules. These are identified as: Granulation 1 (11/8/08-12/9/08), Granulation 2 (3/10/08-14/11/08) and Granulation 3 (1/12/08-16/12/08). All these granulation events occurred in the first year of the project. While there were periods of suspended solids particle size increase during the second year of operation, these were likely caused primarily by increasing floc size and not granule formation.

The conditions present at the start of suspended solids particle size increase and decrease are shown in Table 3.3. For each period, the granulation process was accompanied by a period of high VFA concentration, low prefermenter effluent TSS and COD and medium to high SBR operating temperature (classification of low/medium/high is based on the ranges observed throughout the study).

High VFA concentrations in conjunction with low prefermenter effluent TSS and COD levels appear to be critical to the granulation process in SBR 1. Medium to high SBR temperatures also appear to play a role in this system. These higher temperatures, however, may simply allow faster granule growth due to higher bacterial growth rates and so provide a faster replenishment of granule “seed stock” to offset the granule loss due to washout in the decant.

Table 3.3: Conditions present at the start of SBR 1 sludge particle size increase and decrease.

Granulation Period	**At Start of Granulation**				**At start of loss of Granulation**			
	Feed VFA Conc.	Pref. COD	Pref. TSS	SBR Temp.	Feed VFA Conc.	Pref. COD	Pref. TSS	SBR Temp.
1 (11/8/08-12/9/08)	High	Low	Low-Medium	Medium	Low	High	Medium	Medium
2 (3/10/08-14/11/08)	High	Low	Very Low	High	High	Very high	Very high	High
3 (1/12/08-16/12/08)	High	Low	Low	High	High but dropping	High	High	High

Outside of the highlighted granulation periods, there were periods when several of the postulated "important" conditions were met, but not all and no granulation was observed. For instance prior to granulation 1, there were periods when all conditions were met except for the medium to high temperature and no median particle size increase was observed. Also, in February 2009, the feed VFA concentrations and SBR temperatures were high, but so too was the prefermenter effluent TSS and COD and subsequently no granulation was observed. Throughout most of the remainder of 2009, the VFA concentrations remained low and no granulation was observed.

These observations for the SBR 1 granulation events led to a possible hypothesis to explain how granulation may occur in this system:

- The feeding of VFA into the sludge blanket promotes the production of the exo-cellular polymers (EPS) responsible for the development of the granules (maybe as a carbon storage response to excess VFA provided). Throughout most of the study, visual observation of the sludge (by the naked eye) always showed small granule-like particles present and the sludges always exhibited excellent settling properties (SBR 1 SVI average of 59 $mL.g^{-1}$; SBR 2 SVI average of 74 $mL.g^{-1}$) compared to a typical floccular biomass, suggesting a mixed granular/floccular sludge.
- Under normal conditions of operation, a reactor would not normally be operated with excess VFA fed for the amount of nutrient removal required, as this would only result in unnecessary sludge production. A bottom feed, however, does provide conditions so that the VFA concentration may be in excess within the localized sludge blanket. Thus, under limiting VFA concentrations, a bottom feed is necessary to provide the "granulating" effect of excess VFA.
- The presence of non-VFA rapidly biodegradable COD (such as particulates from the prefermenter) results in rapid floccular growth due to carryover of the COD into the aerobic periods of the cycle. Even at low SRTs, washed out sludge can be quickly replenished in a single cycle if the COD is rapidly degradable (as this study has shown).
- Granule development begins with small granules which grow over time. In the early stages of granulation, the mass of the granules is insufficient to over-come entrapment within typical floccular sludge concentrations and so there is no preferential settling of the granules. If the floccular biomass concentration is sufficiently low, preferential settling of granules over flocs can occur (i.e. when less flocs are present to entrap the developing granules, preferential settling will occur) and this has been observed in laboratory-scale reactors.
- Suspended solids particle size increases observed during granulation events are the net result of granular growth (from localised excess VFA) and granular loss (from the washout of developing granules entrapped within floccular material which is washed out during decant). If the floccular growth is limited (by reducing the amount of non-VFA rapidly biodegradable COD fed), the net result will be an increase in measured sludge particle size due to the growth of the granules.

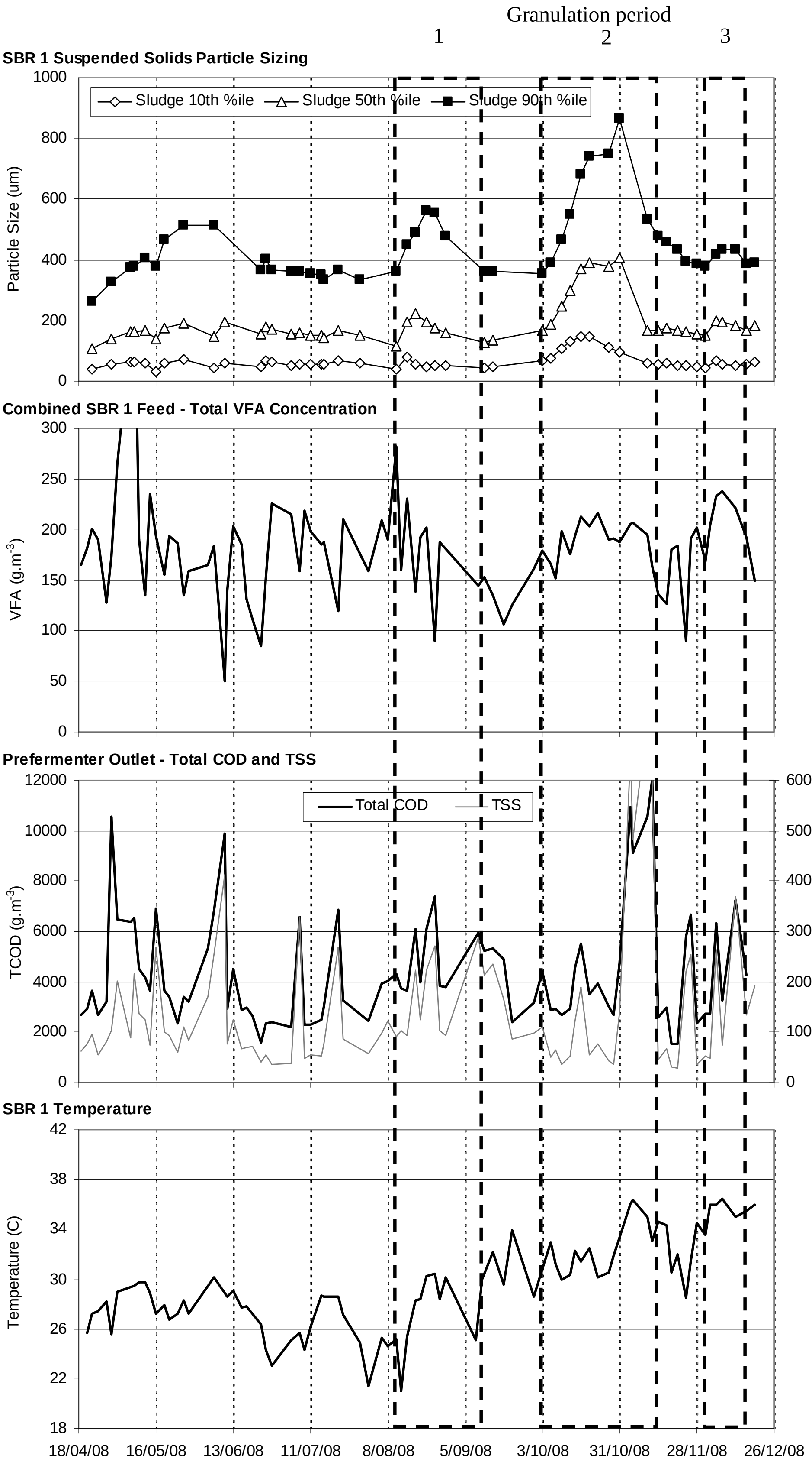


Figure 3.31: SBR 1 suspended solids particle size and temperature with feed VFA concentrations and prefermenter outlet total COD and TSS levels.

While this hypothesis explains the observations of SBR 1, the observations for SBR 2 were more complicated. Data examination of SBR 2 reveals 3 granulation events similar to SBR 1 (Figure 3.32, Table 3.4). However, the timing of these events was slightly different to those of SBR 1. At the start of each granulation event for SBR 2, the prefermenter effluent TCOD and TSS concentrations were always low and the SBR temperature medium to high as for SBR 1. However, the VFA concentration was not always high at the onset of granulation for SBR 2, though it was increasing for granulation 2.

Similarly, at the start of loss of granulation, the prefermenter effluent TCOD and TSS concentrations were not always medium-high as was the case for SBR 1. During granulation 2, the prefermenter effluent COD and TSS levels were both low and so this does not fit well with the above mentioned hypothesis. However, observations made at the time may explain this discrepancy. Particle size reduction for granulation 2 commenced between 6/10/08 and 10/10/08. This period was preceded by observations in the SVI tests showing rising sludge in the last 10-15 minutes of the test (likely caused by denitrification during the settling test causing small N_2 gas bubbles to accumulate in the sludge and make it buoyant). Rising sludge in SVI tests were observed on 3/10/08, 6/10/08, 8/10/08 and 9/10/08 (i.e. in each test performed at this time). On 9/10/08, the DO setpoint was reduced to 1.5 $g.m^{-3}$ for both SBRs and on 10/10/08 no rising sludge was observed.

At the time, SBR 2 was not inspected to see if the rising sludge in the SVI translated to the tank. However, at other times in the project when rising sludge had been observed in the SVI tests, visual inspections of the SBRs also showed rising sludge in the tank, particularly during feeding. Thus, it is likely rising sludge did occur in SBR 2 feeding events just prior to the onset of granule loss in granulation 2. Under these circumstances, the biomass would no longer be exposed to the excess VFA concentrations required (since it is no longer forming a sludge blanket at the bottom of the tank) and so the granulation process would slow or stop. However, since there would still be sludge turnover in the decant, the net result is the loss of granules.

Table 3.4: Conditions present at the start of SBR 2 sludge particle size increase and decrease.

Granulation Period	**At Start of Granulation**				**At start of loss of Granulation**			
	Feed VFA Conc.	Pref. COD	Pref. TSS	SBR Temp.	Feed VFA Conc.	Pref. COD	Pref. TSS	SBR Temp.
1 (10/6/08-21/7/08)	High but variable	Low	Low	Medium	Low	High	High	Medium
2 (12/9/08-20/10/08)	Low but increasing	Low	Low	High	High	Low	Low	High
3 (10/11/08-1/12/08)	High	Low	Low	High	High	Medium but increasing	Medium but increasing	High

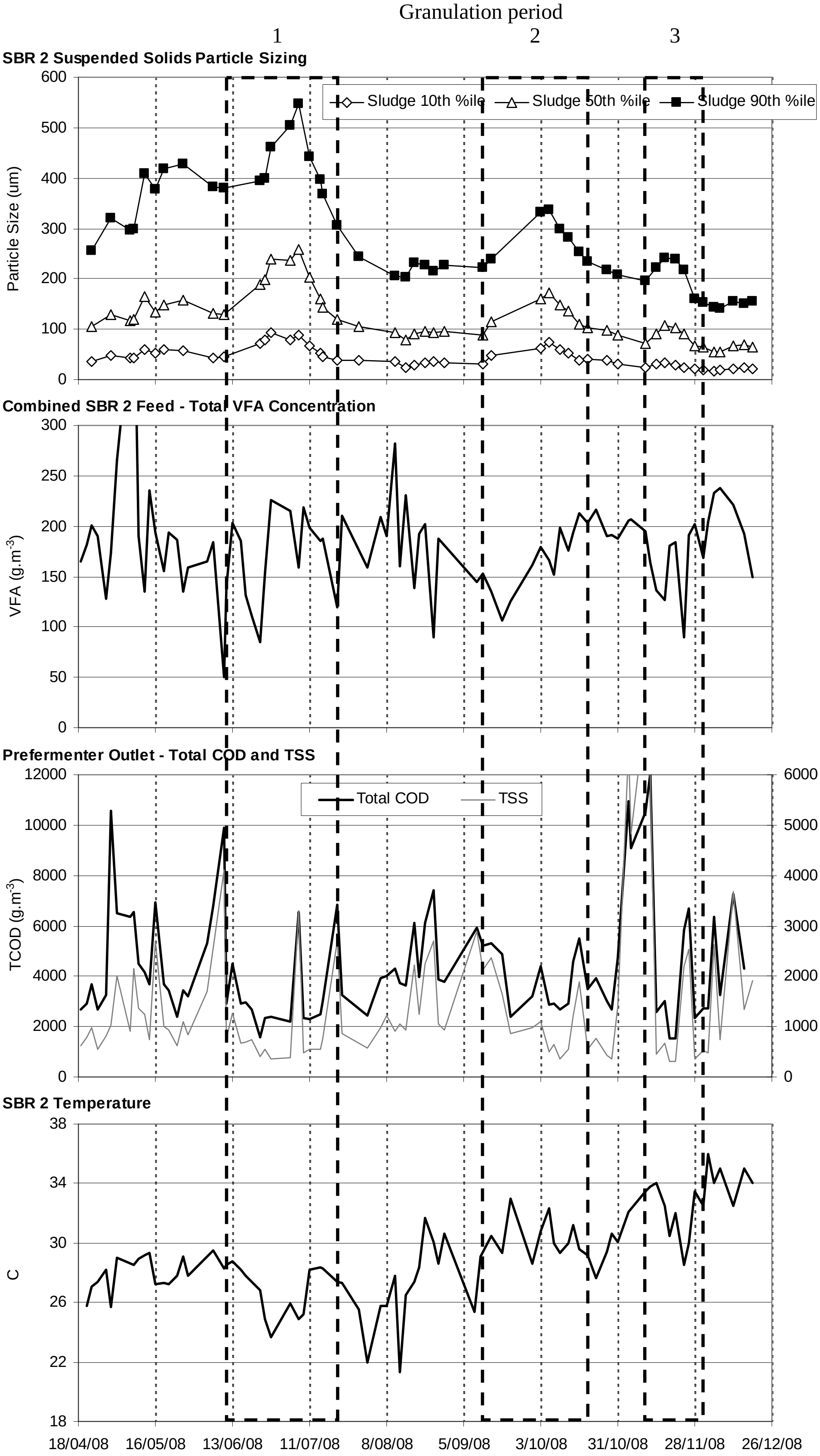


Figure 3.32: SBR 2 suspended solids particle size and temperature with feed VFA concentration and prefermenter outlet total COD and TSS levels.

3.4.2 Importance of the Prefermenter

Apart from the SBR cycle timings and bottom feed arrangement, the prefermenter operation was the most critical aspect of the pilot-plant. While the prefermenter stream represented only 10-20% of the total flow to the pilot-plant, it provided, on average: 47% of the TCOD; >90% of the rapidly biodegradable COD; and 94% of the total VFA.

The performance of the prefermenter was critical to the success of granulation. High VFA concentrations and low particulate COD (represented in the form of TSS) in the prefermenter effluent appear to have been key drivers in the granulation process, with the converse resulting in the washout of these granules.

Achieving high VFAs and low effluent solids from the prefermenter, however, was difficult. The operating temperature of the prefermenter appears to be an important parameter, with higher temperatures (36-40ºC) resulting in higher VFA production. Since the majority of the soluble COD from the prefermenter was always in VFA form, it can be concluded that such higher temperatures increase the rate of particulate hydrolysis, the preliminary step to VFA production.

However, these higher temperatures can also have the adverse effect of preventing the solidification of fats not removed upstream in the DAF. The high temperatures of the “red stream” entering the DAF (45-50ºC) drastically limited the fat removal efficiency, resulting in considerable fats entering the prefermenter (as also observed in the previous project). If these fats remain liquid (and likely dispersed), as is the case at the preferred higher prefermenter temperatures, they affect the settleability of solids (influent particulates and sludge) within the prefermenter. It is likely that these liquid fat (or oil) globules will be adsorbed or otherwise associated with particulates in the water, increasing their buoyancy and hence limiting their settleability.

Investigations aimed at solids reduction during the project were largely unsuccessful. Possibly a better method of operation would be to have two prefermenters operating alternately. While one prefermenter is receiving the DAF flow and generating the VFAs, the other is intermittently mixing (and cooling) without feed and providing the feed source for the SBR, thereby drawing down the volume. These two prefermenters would alternate in their operation (probably every 2 days), thereby providing a continuous flow with likely lower effluent solids.

Another alternative is the removal of some of the heat energy from the “red stream” prior to entry to the DAF. This heat energy could be transferred to the boiler feed water, thereby reducing energy requirements for heating this stream. Reducing the red stream temperature prior to the DAF should assist in the fat removal process and so reduce the fat entering the prefermenter. It could also benefit the solids removal in the DAF.

Whatever method is used, if aerobic granules are to be grown on an abattoir wastewater stream, the prefermenter operation needs to be optimised first, in terms of VFA production and solids settleability. Attempts at optimisation were limited due to time and budgetary restraints, which were not originally factored into this project..

3.4.3 Seeding with Aerobic Granules

While it was difficult to grow aerobic granules with the wastewater, it is likely an aerobic granule seed would be more successful, provided the seed granules have sufficient mass to overcome entrapment within floccular material. This is because the system could be started with a very low settle time at commissioning, preventing the buildup of a highly concentrated floccular sludge. If the cycle exchange ratio is sufficiently high (such as 50%) and cycle length short (3-4 hr), it could be expected that floccular material would not be retained in the system. This would most likely be the case even when high rapidly biodegradable COD is present in the feed. However, if a slowly settling particulate wastewater is fed (such as from an un-optimised prefermenter), it would be reasonable to assume such a fraction would continue in the effluent and require further treatment. Thus, while the system could be fed from an un-optimised prefermenter (in terms of effluent solids), at least some of these solids would then still need to be removed after the SBR.

Currently in Australia, there are no large scale aerobic granulation plants operating to act as a suitable seed material. In the future, when such plants may exist, further investigations could be undertaken to adapt this promising technology for the very challenging abattoir wastewater situations.

3.4.4 SBR Temperature Issues

The relatively short HRT of the Teys Brothers anaerobic pond (5 days) no doubt contributed significantly to the high pond temperatures (and subsequently the SBR temperature) towards the end of the project. The effluent temperature from a more typical abattoir anaerobic pond (with a HRT around 10 days) could be expected to be lower, relieving negative temperature effects in the SBR. Furthermore, abattoirs which experience lower temperatures than sub-tropical regions could also be expected to have lower pond effluent temperatures than experienced at the Teys Brothers site.
Thus, while this site was particularly challenging to implement this technology, particularly during the warmer summer months, other sites may be better suited for this technology.

4 CONCLUSIONS

- Aerobic granules can be developed in an SBR treating Teys Brothers Abattoir wastewater (red stream and anaerobic pond effluent) under certain conditions. These conditions include specific cycle operation, bottom feed delivery to the SBR, high feed VFA concentration (>175 $g.m^{-3}$) and low prefermenter effluent TSS levels (300-600 $g.m^{-3}$ as total feed concentration). When these conditions are maintained and a low settle time imposed, aerobic granules have been observed to develop in the reactors.
- The presence of high concentrations of non-VFA rapidly biodegradable COD during the granule development phase causes excessive floccular growth due to the carry-over of these organics from the anaerobic to the aerobic period. Such growth can entrap developing granules during settling periods and cause a washout of the immature granules during decant.
- Further optimisation of the prefermenter is critical to long-term operation of an aerobic granular system treating abattoir wastewater. In particular, maximising solids settleability and VFA production need to be addressed. Without these optimisations, the growth of aerobic granules in an SBR receiving a combined anaerobic pond effluent and prefermenter feed stream will be very difficult to achieve.
- A hypothesis for granule development in this system was proposed. This hypothesis postulates that biomass particle size increases observed during granulation events are the net result of granular growth (resulting from granule-internal growth based on the storage compounds accumulated under anaerobic conditions from the VFA provided in the feed) and granular loss (from the washout of developing granules entrapped within floccular material which is washed out during decant). This hypothesis seems to adequately reflect observations made in the study.
- Bottom feeding (Unifed system) is critical for granule development to provide localised, maximally concentrated VFA concentrations. Rising sludge during the bottom feeding process will likely result in an insufficient VFA load on the sludge in the SBR and so not result in sufficient internal carbon storage and hence good granule growth.
- Care must be taken when using particle size analysis for determining possible granular development. Breakthrough of VFA (or other rapidly degraded organics) into aerobic periods will result in a temporary biomass particle size increase. However, these increases are not due to granular growth but rather an increasing floc size, with the flocs being quite loose and weak. Microscopic examinations and nutrient removal performance must also be used for determining whether granulation is occurring.
- High anaerobic pond effluent temperatures will adversely affect the nutrient removal processes in an SBR. Loss of phosphorous removal performance occurred at SBR temperatures >36ºC and nitrogen

removal performance at SBR temperatures >38ºC. These effects were observed only when the hydraulic loading was high (1.33 $m^3.m^{-3}.d^{-1}$) and ambient temperatures were high, resulting in high anaerobic pond effluent temperatures.