Contrasting the Benefits of Primary Clarification versus Prefermentation in Activated Sludge Biological Nutrient Removal Systems

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Abstract: The potential benefits prefermentation can provide to biological nutrient removal are measured and compared to the costs of excess oxygen consumption and sludge production incurred by an activated sludge system that utilizes prefermentation, instead of primary clarification. Prefermentation was found to produce superior performance in regards to enhanced biological phosphorus removal. A lower soluble orthophosphorus effluent value [3.2 mg/L for the prefermented activated sludge (PAS) train versus 4.6 mg/L for the control train with primary clarification (PCAS)] and a higher percent phosphorus (% P) content of the biomass (9.0% for the PAS train versus 7.8% for the PCAS train) were both found to be statistically significant (P values of 4.26×10^{-5} and 0.0082, respectively). In addition statistically significant improvements in denitrification rates and reduced observed yields were observed due to prefermentation. However statistically significant increases in solids inventory and in particular oxygen uptake rates offset these improvements. Waste activated sludge production was slightly higher in the PAS train but was not found to be statistically significant.

Introduction

The benefits that primary clarification can provide to wastewater treatment are well known in the literature. Efficiently designed and operated primary clarifiers should remove between 50 and 70% of the suspended solids and 25–40% of the biochemical oxygen demand (BOD) found in the influent (Metcalf and Eddy Inc. 2003). This reduction in solids and BOD loading to an activated sludge process result in lower oxygen consumption, less sludge production, and reduced capital costs. The primary solids removed via primary clarification are sent through the solids-handling system and disposed. These primary solids, however, could potentially have a beneficial use to wastewater treatment via the process of prefermentation.

Enhanced biological phosphorus removal (EBPR) requires the presence of volatile fatty acids (VFAs) in the anaerobic zone of any biological nutrient removal (BNR) wastewater treatment sys-

tem. Unless the sewage is strong and septic (i.e., the influent already has a high VFA concentration) VFAs must be produced. This VFA production is accomplished either within the anaerobic zone of the BNR system or it is done prior to the BNR system in a separate anaerobic process called prefermentation in which hydrolysis and acidogenic fermentation takes place, producing VFAs in a separate step. Prefermenters as a separate unit process were developed by Dr. James Barnard in South Africa along with researchers at the University of Cape Town in the mid-1970s when BNR systems were first developed at full scale. In the United States, however, prefermenters have until recently rarely been considered even when they might arguably have been advantageous. Because of the very few quantitative comparisons of identical systems with and without prefermenters, design engineers often disagree on the necessity of a prefermenter and make decisions based on their prior experience.

Prefermentation of wastewater or primary solids is a common practice associated with BNR facilities in many parts of the world although it is only used in a few full scale installations in the United States to date. Prefermentation technology is associated in the minds of many engineers exclusively with cold climates as an enhancement solely for EBPR for nonseptic wastewaters. It is true that prefermentation technology is used broadly in western Canada for that purpose. However prefermentation is practiced widely in Australia (Keller and Hartley 1997), to some extent in South Africa, and other temperate or even tropical climates.

Prefermenters can be either on-line (the entire wastewater stream is treated) or sidestream (only primary clarifier underflow is treated). The most basic on-line prefermenter is simply a primary clarifier operated with a very high sludge blanket, commonly referred to as a static prefermenter. These prefermenters are not very efficient, often elevating influent VFAs less than more sophisticated prefermenters (Van Munch et al. 1996). Static prefermenters were improved with a recycle to elute VFAs from

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the sludge blanket and this configuration is referred to as an activated primary tank (APT). Sidestream prefermenters are reactors that receive the primary clarifier underflow instead of fermenting the entire wastewater flow. They can consist of a single tank, which may or may not be completely mixed, or of a complete mix tank followed by a dedicated thickener. BNR facilities may receive both prefermented solids and liquid from a sidestream prefermenter, or may receive only the supernatant, depending on which configuration is used. Note that a BNR facility receiving only supernatant flow from a prefermenter will retain some of the benefits of primary clarification (e.g., primary solids removed by the primary clarifier) while still retaining the enhanced VFA benefits.

Traditionally the function of prefermenters has been to convert a large portion of the slowly degradable influent chemical oxygen demand (COD) into readily available substrate (e.g., VFAs) to drive EBPR in the anaerobic zone. In plants in western Canada, where prefermentation is very common, consistent effluents of 0.5 mg/L and lower are claimed without chemical polishing for some wastewaters. Reliably going below 1 mg/L without chemical polishing is anecdotally described as routine. However there are obvious disadvantages to prefermentation. One is that the capital costs of primary clarification are incurred while many of the benefits may be lost (i.e., no direct reduction in oxygen demand or secondary waste sludge production although increased denitrification may mitigate this). In addition in countries where there is a phosphate detergent ban such as the United States, it is not as difficult to meet effluent standards and chemical polishing costs can be significantly less than in countries with significantly higher influent phosphorus concentrations. Further in the southern United States, and seasonally in the north, raw wastewater is often at least partially septic, and in Florida it is very septic and raw wastewater concentrations may routinely exceed 50 mg/L total VFAs even in the winter. As a result it is often presumed that there will be little benefit to prefermentation in a warm climate.

Prefermenters have historically been frequently used with BNR plants by some design communities, while other design communities have not (at least in the past) seriously considered them as an option. Part of the reason for this is the absence of quantitative information on the process and effluent changes resulting from prefermentation for a variety of wastewaters and climates. Most information is from full scale applications and is anecdotal [e.g., we have a plant with prefermentation that always meets 0.5 mg/L phosphorus (P), we have a plant without prefermentation that always goes below 1 mg/L P, etc.], with only a few direct comparisons existing in the literature (e.g., Danesh and Oleszkiewicz 1997).

This pilot scale study was conducted with the basic objective of quantifying benefits to BNR of prefermentation and contrasting them with increased oxygen consumption and sludge production one would expect when compared to a system that utilized primary clarification.

Materials and Methods

Pilot Scale System

In order to compare and contrast the potential benefits of prefermentation to BNR against the well known benefits of primary clarification (e.g., lower oxygen consumption rates, less secondary waste sludge production, etc.), two parallel pilot scale activated sludge wastewater treatment trains were constructed. The
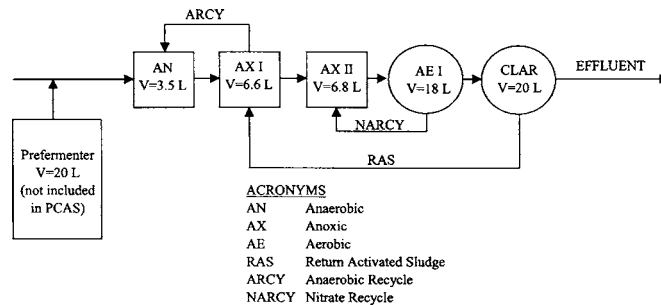

Fig. 1. Schematic of PAS pilot scale system

prefermented activated sludge (PAS) train, received raw influent augmented with prefermented primary solids from an off-line static prefermenter. Primary solids taken from a full scale municipal wastewater treatment plant (WWTP) primary clarifier in central Florida (Altamonte Springs Water Reclamation Facility, Altamonte Springs, Fla.) were used to feed the experimental off-line prefermenter. The off-line prefermenter which had a liquid volume of 20 L, was maintained at a solids retention time (SRT) of 10 days. The second activated sludge pilot train, which did not receive any additional primary solids, was called the primary clarification activated sludge (PCAS) system. The lack of primary solids addition to the PCAS system was intended to resemble an influent that received primary clarification, when compared to the PAS train influent, which contained extra primary solids COD that passed through the off-line static prefermenter.

The flow configuration selected for the activated sludge systems of the pilot scale WWTP was the modified University of Cape Town (MUCT) configuration for biological nutrient removal, and is shown in Fig. 1 for the PAS pilot train. The MUCT configuration is similar to that of the University of Cape Town (UCT) configuration, with the exception that an extra anoxic zone is included. The first anoxic zone receives the return activated sludge (RAS), while the second anoxic zone received the nitrate recycle (NARCY). The anaerobic recycle (ARCY) returns biomass from the first anoxic zone to the anaerobic zone. The purpose of the first anoxic zone is to provide extra protection to the anaerobic zone by further depleting the oxygen and nitrates which might be present in the RAS. Note that the PCAS train is identical to the PAS train, except for the lack of primary solids addition from the off-line static prefermenter. Influent flows averaged 247.2 L/day for the PAS train, and 248.3 L/day for the PCAS train. Recirculation rates were $1Q$ for the ARCY, $3.1Q$ for the NARCY, and $0.7Q$ for the RAS. The PAS train was operated at an SRT of 9.0 days, and a hydraulic retention time (HRT) of 3.4 h, while the PCAS train was operated at an SRT of 8.8 days, and an HRT of 3.5 h.

The pilot scale systems were operated within the East Orange County Water Reclamation Facility or EOCWRF (Orange County, Fla.) in an enclosed room with access to a tap with raw domestic wastewater. Fresh influent was provided for the systems daily by two separate polyethylene tanks, one for the PAS train and one for the PCAS train, with raw influent wastewater. Two Liters per day of prefermented primary solids was added to the PAS influent tank. Sufficient phosphorus was added to both influents to make them COD-limited (total COD:total P ratio less than 40:1), instead of the wastewater's natural P-limited state (TCOD:TP ratio greater than 40:1), thus making differences in enhanced biological phosphorus removal (EBPR) easier to identify for this septic (e.g., high VFA content) wastewater (WEF

1998). At the end of a daily cycle, any remaining influent was dumped and the sides of the influent tank were scrubbed prior to the addition of fresh influent. A single submersible pump (Little Giant Pump Co., Oklahoma City) provided the mixing energy necessary to keep each influent tank sufficiently mixed. Peristaltic pumps manufactured by Cole-Parmer Instrument Company (Vernon Hills, Ill.) were used to maintain design flow rates for the influent line and all recycle lines. Mixing energy for both the anaerobic and anoxic zones of the activated sludge systems was provided by 50-rpm gear motors (Grainger, Lake Forest, Ill.). Aquarium aerators (Rena, Annecy, France) provided mixing energy for the aerobic zones, as well as aeration. The secondary clarifiers had surface skimmers and bottom scrapers powered by 1-rpm gear motors (Grainger, Lake Forest, Ill.), and were constructed from 50-L cylindrical tanks with a conical bottom. The off-line prefermenter was constructed from a 20-L cylindrical polyethylene storage container. The anaerobic and anoxic zones of the activated sludge reactor were constructed from 8-in.^{2} polyethylene reactors, with each reactor having a liquid volume of approximately 7 L. The aerobic zone activated sludge reactors were constructed from 20-L cylindrical polyethylene reactors. The entire activated sludge system was hard-plumbed with 1-in.-diameter schedule 40 polyvinyl chloride (PVC). A series of 1-in. ball valves allowed for the rerouting of flows to multiple locations, as desired by the operators. These ball valves allowed for multiple recycle line exit points, a bypass line for the first anaerobic zone, and split-feed lines to allow for step feeding.

Cleaning techniques were also found to be of tremendous importance in maintaining stable operation of the pilot system. Specifically, a daily scrubbing of the sidewalls of all reactors of the activated sludge system, especially the aerobic tank, was necessary to prevent the buildup of a biofilm along the walls of the reactors. The sidewalls of the secondary clarifiers were also gently scraped above the sludge blanket on a daily basis. This was necessary in order to maintain a more consistent effluent solids concentration. Specifically, if the sidewalls of the secondary clarifier were not scraped daily, a biofilm would accumulate on the sidewalls, and would eventually slough off, thereby elevating the effluent solids concentration. It was also important to clean the 1-in. PVC lines connecting the anaerobic, anoxic, and aerobic tanks together, as biofilms could easily grow in those lines. To prevent clogging, the barb fitting where the 1-in. PVC was connected to the 3/8-in. i.d. neoprene tubing was periodically brushed clean. This connection was located where the neoprene tubing passed through the peristaltic pump head.

Chemical Analysis

Total suspended solids (TSS) and volatile suspended solids (VSS) were determined according to standard methods (APHA et al. 1995). Total phosphorus (TP) samples underwent persulfate digestion as outlined in standard methods 4500-P B(5), followed by the vanadomolybdophosphoric acid colorimetric method 4500-P C (APHA et al. 1995). Soluble orthophosphorus (SOP) was determined using the vanadomolybdophosphoric acid colorimetric method 4500-P C in standard methods (APHA et al. 1995). COD was determined by following section 5220 C in standard methods (APHA et al. 1995). Organic nitrogen (both total Kjeldahl nitrogen and soluble Kjeldahl nitrogen) and ammonia nitrogen were analyzed by methods 4500-N$_{org}$ A and 4500-NH$_3$ C, respectively, of standard methods (APHA et al. 1995). Nitrate was determined using a Dionex 2000 I/SP ion chromatograph (Sunnyvale, Calif.) with a CDM-3 conductivity detector and a 4270 integrator using a

method similar to that found in standard methods 4500-NO$_3$ C (APHA et al. 1995). Samples were analyzed for short-chain volatile fatty acids (SCVFAs) following Supelco Bulletin 856B (Supelco 1995) using gas chromatography. A Shimadzu gas chromatograph model 14-A (Shimadzu Scientific Instruments, Inc., Columbia, Md.) equipped with a flame ionization detector (FID) was utilized to conduct the analysis. A 3-mm-inner diameter glass column with 60/80 Carbopack C/0.3% Carbowax 20M/0.1%H$_3$PO$_4$ packing (Supelco Inc., Bellefonte, Pa.) was used to separate the various SCVFAs. Helium, at approximately 30 mL/min, was selected as the carrier gas. The injection port and the FID were maintained at 200°C. The oven of the gas chromatograph was programmed to begin sample analysis at 105°C, remaining at 105°C for 2 min, before increasing at a rate of 5°C/min to 150°C, and to hold at 150°C for an additional 2 min, resulting in a total run time of 13 min/sample. Polyhydroxyalkanoates (PHAs) were analyzed by a gas chromatographic method (Liu 2001) using a DB-1 capillary column. The predominant forms of PHA that were measured were poly-β-hydroxybutyrate (PHB) and poly-β-hydroxyvalerate (PHV). The carrier gas, helium was maintained at a velocity of 2 mL/min and as the makeup gas (25 mL/min). The injection port and detector were maintained at a temperature of 230°C. The column temperature started at 100°C for 2 min, was increased by 20°C/min to 160°C, and maintained at 160°C for an additional 10 min, resulting in a run time of 15 min. Prior to injection, sludge samples were freeze dried using a lyophilizer and then run through a digestion. About 0.15 g of dry sludge was put into 5.0 mL Wheaton V vials. Two mL of benzoic acid in chloroform (50 mg/100 mL) was added to the vial for use as an internal standard and solvent, respectively. Next, 2 mL of 20% H$_2$SO$_4$ in methanol was added as the digestion/esterification reagent (methyl esters of the PHA are what is actually extracted into the chloroform phase). The vials were then placed inverted into a 100°C oven for 18 h. Early during the digestion (within 2 h of starting), vial caps were retightened, in order to minimize the chance of leakage. Additionally, duplicates were run of all samples, as approximately 10% of the vials develop leaks during the digestion process. After cooling to room temperature, 1 mL of deionized water is added to the vial, and the contents of the vial are shaken using a vortexer (Fisher Scientific, Hampton, N.H.) for 5 min. Once the 5-min washing phase was completed, the chloroform phase was removed from the vial and placed into a 1.5 mL gas chromatography (GC) vial for injection. Carbohydrates were determined by the anthrone method (ASM 1981). Readily biodegradable chemical oxygen demand (RBCOD) was determined following techniques developed both by Ekama et al. (1986) and Wentzel et al. (1995).

Sample Collection and Monitoring

During all phases of this research project, activated sludge trains were operated until steady-state conditions were met [i.e., greater than three mean cell residence times (MCRTs)]. The data presented in this paper reflect the results of nine separate sampling events conducted over a 3-week period. Composite samplers (Isco Inc., Lincoln, Neb.) were used on influent samples. All other samples taken during the study were grab samples. All sample analyses were conducted within 24 h after sampling (most within 4 h), so beyond refrigeration, no sample storage protocols were established (e.g., no acid additions). All samples were filtered immediately upon removal from the activated sludge system. Mixed liquor reactor samples were first centrifuged on site imme-

diately after sampling, then filtered with Whatman 934 AH glass fiber filters, and finally membrane filtered with 0.45-μm membrane filters. Field parameters, such as dissolved oxygen (DO), pH, temperature, sludge volume index (SVI), zone settling velocity (ZSV), and both in situ and ex situ oxygen uptake rates (OURs) were run concurrently with sampling events during the pilot scale study.

The results of the analytical tests were statistically analyzed using a paired difference test in which the means of various parameters were compared between the two trains (Mendenhall and Sincich 1995). Differences were assumed to be significant if the *p* values were less than 0.1. However, along with any statements of statistical significance, the actual *p* value is also reported. In all figures, error bars with ±1 SD are shown.

Results

Effects upon Influent Characteristics

Composite samplers (Isco Inc., Lincoln, Neb.) on both the influent tanks allowed for the impact of prefermentation upon influent characteristics to be compared to an influent that underwent primary clarification. Specifically, prefermentation was found to increase the VFA content of within the prefermented AS train influent by 17.7 mg/L as COD (an increase of 26.4%). Note that the control train with primary clarification influent wastewater was already highly septic, with a VFA content averaging 67.0 mg/L as COD. The only VFAs detected in the influent tanks were acetate and propionate. Prefermentation was not found to significantly alter the ratio of acetate to propionate within the influent in this study, with acetate content averaging approximately 66% of the VFAs as COD for both the prefermented train and the control train influent. Additionally, prefermentation was also found to significantly increase the RBCOD content found within the influent wastewater. Prefermentation increased the RBCOD content of the PAS influent by 31.9% (from 94 mg/L in the PCAS influent to 124 mg/L for the PAS influent).

Effects upon EBPR

One of the major results of the pilot scale study was that for this septic, COD-limited wastewater prefermentation increased the net P removal when compared to a control train with primary clarification, which is the ultimate objective of EBPR. Fig. 2 compares the SOP profiles of the PAS and PCAS.

The effluent soluble orthophosphorus for the control train with primary clarification (PCAS) was nearly 44% higher than that of the prefermented train (PAS). Using a paired difference test between two population means, it can be shown that the effluent phosphorus concentration for the PAS train (3.2 mg/L) was statistically superior to that of the PCAS train (4.6 mg/L) with a *p* value of 4.26×10^{-5} (Mendenhall and Sincich 1995). This result is not surprising, as the PAS train received influent that was richer in both VFA and RBCOND content than the PCAS train.

Both trains had sufficient VFA content to drive EBPR. The literature indicates a VFA:TP ratio of between 4 and 10 mg VFA per milligram of P is necessary for good phosphorus removal. Metcalf and Eddy (2003) cites a conservative 10:1 ratio of VFA:P, while Daigger and Bowen (1994) and anecdotal suggestions specify VFA:TP rations of 7:1 and 4:1, respectively. Much of the seeming contradictions in the literature may be due to temperature. Generally, the 4:1 ratio applies to western Canada where
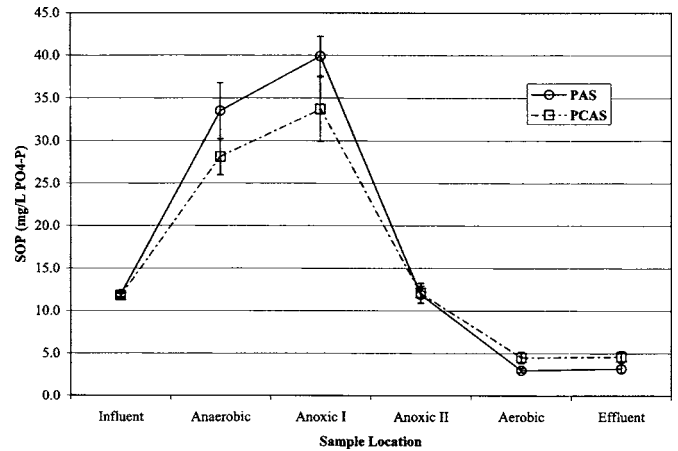

Fig. 2. SOP profile for PAS and PCAS trains

there are cold but stable temperatures allowing for psychrophilic EBPR. The temperatures found in this study were quite elevated in contrast, averaging 28.0°C. In this study, the VFA:TP ratio was observed to be 7.1 for the PAS train, and 5.7 for the CAS train. Since increasing the VFA:TP ratio from 5.7 to 7.1 resulted in improved EBPR, the data were more consistent with the midrange or high ratios in the literature (i.e., a VFA:TP ratio greater than 5.7:1 provides benefits to EBPR).

An analysis of the mass flux of phosphorus through the individual reactors of the pilot systems yields additional insight into the potential of prefermentation to increase P removal when compared to an activated sludge system that has a primary clarifier. Table 1 shows the results of this mass flux analysis on phosphorus.

When comparing the % P in MLSS as calculated via a mass balance, it can be seen that prefermentation increased the % P content of MLSS (9.0 versus 7.8% for the control train, which is a statistically significant difference with a P value of 0.0082). This correlated with the lower effluent SOP profiles shown in Fig. 2. Of further interest is the marked difference in SOP release and uptake between the PAS and PCAS trains. The PAS trains had 42.8% greater SOP release in the anaerobic zone than the PCAS train. This correlated with the greater amount of VFAs found within the PAS train due to prefermentation. In addition, superior SOP uptake in both Anoxic II and the aerobic zone of the PAS train when compared to the PCAS train was noted. Specifically, a

Table 1. Phosphorus Mass Flux Values for PAS and PCAS Trains

Parameters (mg/day)	PAS train	PCAS train
TP influent	2,912.0	2,901.3
Anaerobic SOP release	3,693.7	2,584.9
Anoxic I SOP release	9,629.8	7,865.5
Anoxic II SOP uptake	5,023.2	3,320.8
Net SOP anoxic release	4,606.6	4,544.7
Total SOP release	13,323.5	10,450.4
Aerobic SOP uptake	10,502.1	8,934.2
Clarifier SOP release	77.6	27.9
Total SOP uptake	15,447.7	12,227.1
SOP uptake:SOP release ratio	1.16	1.17
Net SOP uptake	2,124.2	1,776.7
P in MLSS as calculated via mass balance (%)	9.0	7.8

Fig. 3. PHA profile for PAS and PCAS trains

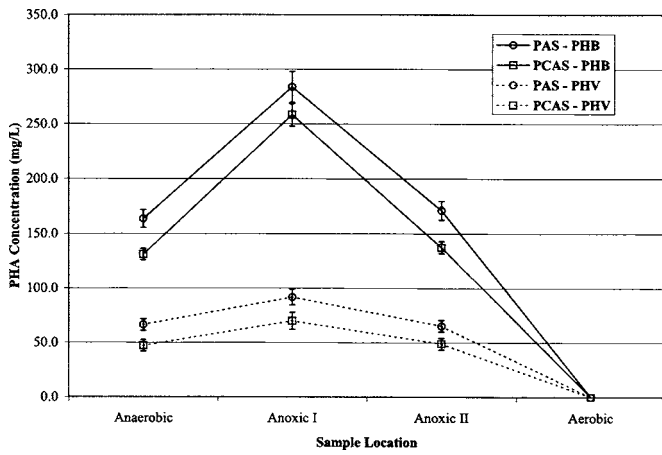**Fig. 5.** Nitrate profile

27.5% increase in the total SOP release and a 26.3% increase in the total SOP uptake was found in the PAS train as compared to the PCAS train. However, despite the differences in phosphorus release and uptake between the two trains, the SOP uptake: SOP release ratios were remarkably similar (1.16 for the PAS train and 1.17 for the PCAS train), as shown in Table 1.

Other parameters of importance to EBPR were also measured, including polyhydroxyalkanoates, or PHAs (both PHB and PHV), and glycogen. Both PHA and glycogen concentrations were higher in the PAS train as compared to the PCAS train. Figs. 3 and 4, respectively, show the PHA and glycogen profiles for both the PAS and PCAS trains. Note that the apparent increase in the concentration of glycogen from the anaerobic zone to Anoxic I is an artifact of the MUCT flow configuration. A mass flux analysis of glycogen indicated there is glycogen depletion across both the anaerobic zone and Anoxic I, which corresponds to the increase in PHA concentrations illustrated in Fig. 3.

Effects of Prefermentation on Denitrification and N Mass Balances

Nitrogen forms, including nitrate (NO_3-N), ammonia (NH_4-N), soluble Kjeldahl nitrogen, and total Kjeldahl nitrogen, were measured during the course of this study. All phases had similar ni-

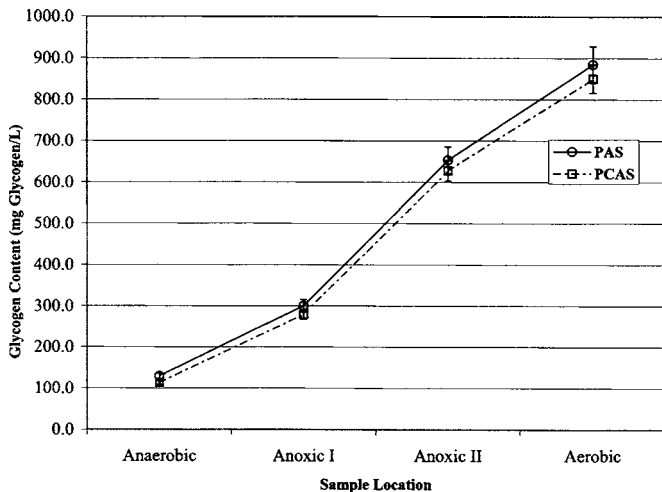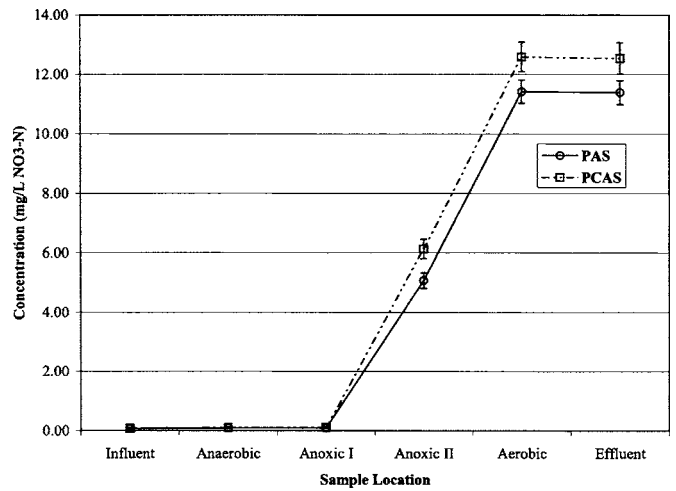**Fig. 4.** Glycogen profile for PAS and PCAS trains

trogen profiles for all nitrogen (N) forms, with differences coming only in the absolute values of the measured parameters. The greatest difference in concentration of N forms measured during this study was found in the effluent nitrate values. Fig. 5 shows a comparison of the nitrate profiles of the two trains.

The prefermented (PAS) train had an effluent nitrate concentration of 11.4 mg/L NO_3-N, as compared to a 12.5 mg/L value for the control train with primary clarification (PCAS) train, which amounts to only a 5% difference. However, despite the small absolute value of the difference in the effluent nitrate concentration between the two trains, the difference between the two means had statistical significance, with p value of 4.26×10^{-5} (Mendenhall and Sincich 1995).

Nitrogen mass balances were conducted upon the data generated during this study in order to verify the quality of the data collected, using the following equation:

$$\Sigma TN_{influent} = \Sigma \Delta NO_{3 \text{ denitrified}} + N_{assimilated} + \Sigma SN_{effluent/WAS}$$

(1)

where $\Sigma TN_{influent}$=sum of total nitrogen in the influent (mg/day); $\Sigma \Delta NO_{3 \text{ denitrified}}$=sum of nitrate denitrified in unaerated zones (mg/day); $N_{assimiiated}$=nitrogen assimilated into growth of new biomass (mg/day); and $\Sigma SN_{effluent/WAS}$=sum of soluble nitrogen in the effluent and waste activated sludge (mg/day).

Table 2 shows the results of nitrogen mass balances conducted during this study: Of particular interest is the good agreement found in the nitrogen mass balances, with a 98.0% agreement in the PAS train and a 101.7% for the PCAS train, easily within the error of the measurements. Note that the nitrogen mass balances rely upon an assumed fraction of N in biomass (f_N) of 0.1239 which is a common assumed value reflecting the average composition of activated sludge biomass used in the environmental engineering community (Metcalf and Eddy Inc. 2003). A sensitivity analysis was also conducted over a broader range of possible values based on the literature, and mass balance agreements were still above 93.8% even with an N content of 0.10. Also note that Eq. (1) assumed that all nitrate disappearance is attributed to N_2 formation, not nitrite formation, ammonia formation via dissimilatory reduction of nitrate to ammonia (DNRA), or biological assimilation of nitrate.

Evaluation of the effect of prefermentation upon denitrification when compared to a system that has primary clarification was one of the main objectives of this study. Table 3 compares specific

Table 2. Nitrogen Mass Balance

Parameters (mg/day)	PAS	PCAS
TN influent	10,597	10,424
Assimilated N[a,b]	2,270	2,201
Nitrate load to unaerated zones	10,786	11,888
Nitrate load leaving unaerated zones	6,036	7,305
Unaerated zones denitrification	4,749	4,583
Soluble nitrogen in effluent and WAS	3,360	3,809
Secondary clarifier denitrification	16	24
N mass balance agreement (%)	98.0	101.7
Simultaneous denitrification/discrepancy[c]	226	−213

[a]Assumes f_N (nitrogen content of biomass)=0.1239.
[b]Includes solids wasted, and in effluent.
[c]Calculated by difference.

Table 4. Comparison between PAS and PCAS Trains upon Parameters That Measure Oxygen Consumption and Sludge Production

Parameter	PAS	PCAS	PAS larger than PCAS (%)	P value
OUR (mg/L/h)	101.4	84.0	20.7	3.52×10^{-4}
SOUR (mg/g/h)	19.9	18.0	10.6	0.027
WAS production (mg/day)	18,251	17,704	3.1	0.145
MLSS inventory (mg)	213,571	201,344	6.1	5.72×10^{-5}
MLVSS inventory (mg)	163,498	154,225	6.0	1.48×10^{-4}
FSS inventory (mg)	50,073	47,119	6.3	0.0110
Observed yield (mg VSS/mg COD)	0.249	0.266	−6.4	0.0545

anoxic denitrification rates measured in both anoxic zones of the pilot systems. Actual denitrification rates could not be observed in Anoxic I zones since they were not fully loaded with NO_x, as Fig. 5 indicates that both trains had little measurable NO_x. However in the Anoxic II zones actual denitrification capacities could be observed since the zones were overloaded with NO_x. In this pilot study, the prefermented (PAS) train had a 13.3% greater specific denitrification rate in the second anoxic zone than the control train (PCAS) train. This difference between the average Anoxic II specific denitrification rates had statistical significance, with a p value of 0.0028. This result corresponded to an influent richer in VFAs and RBCOD resulting in higher specific rates in the zone where the bulk of the denitrification in the system occurs.

Effects upon Oxygen Consumption, Sludge Production, and COD Mass Balance

The previous two sections of this paper outline the benefits to BNR that prefermentation can have, when compared to an activated sludge system that has primary clarification. However, the superior BNR performance comes at the cost of increased oxygen consumption, sludge production, and increased capital costs (increased tankage volume, for example) due to extra COD loading found in an activated sludge train with a prefermenter, when compared to an activated sludge train with primary clarification. A comparison between the train with a prefermenter (PAS) and the control train with a primary clarifier (PCAS) for various parameters that measure oxygen consumption and sludge production are shown in Table 4.

The P value column in Table 4 refers to the results of a paired difference test in which the means are compared (Mendenhall and Sincich 1995). Significant differences between the prefermented train (PAS) and the control train with primary clarification (PCAS) can be found in the OUR, specific oxygen uptake rate (SOUR), and the mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), and fixed suspended solids (FSS) inventories. All of these values indicate that in-

Table 3. Specific Anoxic Zone Denitrification Rates in Pilot Scale Study (mg NO_x/g VSS·Day)

Train	Anoxic I	Anoxic II
PAS	>66.8	80.8
PCAS	>73.9	71.3

creased oxygen costs can be expected while operating an activated sludge train with prefermentation, when compared to an activated sludge train that has primary clarification.

While the PAS train was found to have 3.1% more waste activated sludge (WAS) production, this difference was not found to be statistically significant, having a p value of only 0.144. The PCAS train was actually found to have a 6.4% higher average observed yield than the PAS train, with a p level of 0.0545. While the PAS train has slightly larger WAS production than the PCAS train, the PAS train also had much higher ΔCOD than the PCAS train, thus explaining the lower observed yields found in the PAS train. Additionally, acetic acid is highly oxidized and a low yield substrate, and its reduction to PHA comes at a glycogen cost (Yellore et al. 1999). It may be that while fermentation of COD to acetic and propionic acid does not result in a COD loss, with respect to oxygen demand, it does result in a form of compound with lower yield characteristics since it has in fact been metabolized and resulted in anaerobic yield among the fermenters.

COD mass balances resulted in poor agreement, unlike the N mass balances. Percent agreement values for the COD mass balances were only 74.1% for the prefermented (PAS) train and 70.5% for the control train with primary clarification (PCAS) train. A profile of the soluble COD across each train is shown in Fig. 6. Other researchers, including Barker and Dold (1995), have found similar poor COD mass balances agreement around activated sludge systems that include an anaerobic zone. In parallel anoxic/aerobic and aerobic activated sludge systems, Barker and Dold (1995) were able to achieve good COD mass balance agreement, but this agreement failed once an anaerobic zone was added. This identified a process occurring in the anaerobic zone as a potential cause of the poor COD mass balance agreements found in activated sludge systems with anaerobic zones. Given the quality of our N mass balances (again, assuming an f_N of 0.1239), analytical error of this magnitude seems unlikely. This COD mass balance discrepancy may have been due to the poorly understood and controversial phenomena of "anaerobic stabilization" (loss of COD in anaerobic zones; Randall et al. 1992; Barker and Dold 1995).
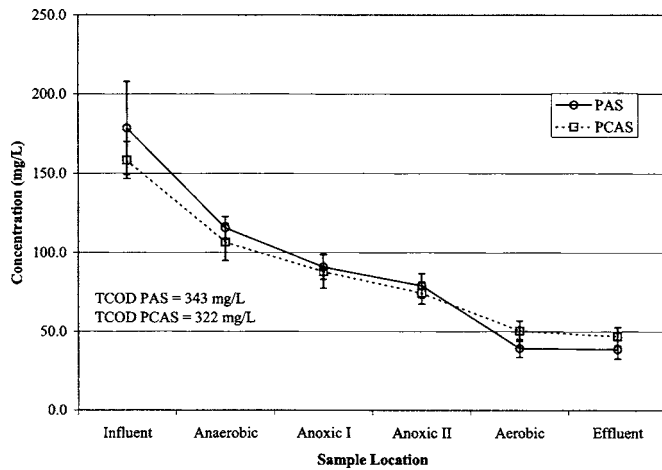
Fig. 6. Soluble COD profile

Conclusions

The following numbered list summarizes the important findings developed during the course of the comparison of an activated sludge system with prefermentation (PAS) to an activated sludge system with primary clarification (PCAS):

1. Prefermentation was found to produce superior performance in regards to EBPR. A lower SOP effluent value (3.2 mg/L for the PAS train versus 4.6 mg/L for the PCAS train) and a higher % P content of the biomass (9.0% for the PAS train versus 7.8% for the PCAS train) was found to be statistically significant;

2. The increased anaerobic P release and aerobic P uptakes due to prefermentation correlated with greater PHA formation and glycogen consumption during anaerobiosis of prefermented influent in the PAS train when compared to the PCAS trains;

3. Prefermentation increased RBCOD content by an average of 31.9% and VFA content by an average of 26.4% when compared to a septic system with primary clarification;

4. Increasing the VFA:TP ratio from 5.7 to 7.1 at 28.0°C improved EBPR, which was consistent with the design criteria published in the United States but not with the lower values from design experience in western Canada;

5. Oxygen utilization rates and specific oxygen utilization rates were found to be 20.7 and 11.1% higher, respectively, for the PAS train as compared to the PCAS train. These results were statistically significant, with p values of 3.52×10^{-4} and 0.0274, respectively;

6. Statistically significant increases in MLSS (6.0%), MLVSS (6.1%), and FSS (6.3%) inventories were found in the PAS train as compared to the PCAS train;

7. An increase (3.1%) in WAS production in the PAS train when compared to the PCAS train was not found to be statistically significant (p value of 0.144);

8. Observed yields were larger (6.4%) in the PCAS train, as compared to the PAS train, with a p value of 0.0545; and

9. The relative cost/benefit of improved effluent SOP and TN of prefermentation are partly offset by the increased oxygen demands of returned primary solids COD as SCVFAs. WAS

however was not observed to increase in the same way, although future studies should be conducted for confirmation. This phenomena could be due to the energy poor nature of acetic acid (Yellore et al. 1999).

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