Implementing Hydrocyclones in Mainstream Process for Enhancing Biological Phosphorus Removal and Increasing Settleability through Aerobic Granulation.

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INTRODUCTION:

Aerobic granules, which do not require bio-flocculation for settling, serve as a stratified microbiome for polyphosphate accumulating organisms (PAO), ammonia oxidizing bacteria (AOB), nitrite oxidizing bacteria (NOBs), denitrifying heterotrophs, and in some applications, anaerobic ammonia oxidizers (anammox). This stratification allows for substrate diffusion forming aerobic, anoxic, and anaerobic layers in which favorable conditions are generated for enhancing carbon and biological nutrient removal within a single biofilm. The aerobic granules have a higher density than flocs due to the retention of inorganic materials in the granule core. (Winkler et al., 2013). Sears et al.(2006) investigated the correlation between density and settling rates and found flocs with poor settling of < 5 m/hr had densities of 1.038 to 1.041 g/mL, aggregates with settling between 5 and 30 m/hr had densities of 1.041 to 1.049 g/mL, while excellent settling spherical granules settling at > 30 m/hr had densities between 1.060 to 1.065. In addition, activated sludge that underwent anaerobic digestion had densities between 1.11 to 1.12 g/mL, which was attributed to inorganic content. Increased density leads to improved settling characteristics which allows for the prevention of biomass loss and subsequent treatment disruption, especially during wet weather scenarios. Selection for faster settling particles and shear force encourages aerobic granular sludge growth that can be provided by hydrocyclones, which receive mixed liquor tangentially and separate light solids from more dense solids through their tapered shape. Increasing the velocity of liquid as it moves downward allows for selection of a certain desired solids fraction. The hydrocyclones select for dense granules through the underflow while the lighter solids are wasted via the overflow. The use of an external selector for improving settleability and stabilizing biological phosphorus removal (bioP), without the use of a formal anaerobic selector, is a
low capital cost investment for wastewater treatment plants. Denitrifying PAOs (dPAO); utilizing either nitrate or nitrite as their electron donor during phosphorus uptake, excel in granule formation which leads to increased competition over of glycogen-accumulating organisms (GAOs) (de Kreuk et al., 2005). DPAOs lead to more efficient treatment by effectively utilizing COD for both nitrogen and phosphorus removal from the bulk liquid. Achieving reliable bioP with the aerobic granules allows for reduction in metal salt addition and, if operating in a low alkalinity system, a further reduction in caustic addition can occur.

The Hampton Roads Sanitation District’s (HRSD) James River Wastewater Treatment Plant (JRWWTP) located in Newport News, VA rated at 20 MGD, utilizes a 4-stage Bardenpho configuration with an Integrated Fixed Film System (IFAS) (Figure 1). The ammonia and phosphorus load in centrate from the anaerobic digesters is treated with AnitaMox™ and ferric sulphate addition, respectively. The utilization of IFAS allows nitrification while maintaining an aerobic solids retention time (SRT) of 1.5 to 3.5 days, thus causing unstable biological phosphorus removal. The plant has had historically poor settleability with SVI₃₀ of 140-150 mL/g. The poor settling could not be associated with filament problems but instead attributed to shallow peripheral feed clarifiers with imbalanced hydraulic splits.

Therefore the objectives of the research were to evaluate the World Water Works™ (WWW) inDense™ process for improving settleability and stabilizing bioP removal.

Figure 1: James River WWTP process overview.
**METHODOLOGY:**

**Hydrocyclone Installation and Operation:**

Starting March 2015, eight 20 m³/hr hydrocyclones were installed and continuously operated with the exception of a small shut down period during the month of May, 2015. The hydrocyclones are fed a portion of the return activated sludge (RAS) and the feed rate is based upon the targeted wasting for JRWWTP since the lighter poorer settling solids from the overflow serve as the waste activated sludge (WAS). The more dense particles are mixed with the primary clarifier effluent (PCE) and returned to the beginning of the aeration influent (Figure 2).

![Hydraulic flow diagram for hydrocyclone operation](image)

*Figure 2: Hydraulic flow diagram for hydrocyclone operation*
Testing and analysis:

The settled sludge volume (SSV) and sludge volume index (SVI) established by Mohlman, 1934 functions as a standard tool utilized by WWTPs to characterize the physical conditions of activated sludge and the impacts on settleability. Daily measurements for SSV\textsubscript{5}, SSV\textsubscript{30}, SVI\textsubscript{5}, and SVI\textsubscript{30} were collected on the aeration ML to identify increased settling stability and overall improvement. Routine measurements were collected on the underflow and overflow to ensure poorer settling flocs were being wasted while denser particles from the underflow are recycled to the aeration basin. To further investigate the settling characteristics initial/zone settling velocity (ISV/ ZSV) analysis was conducted on the aeration effluent, overflow, and underflow mixed liquor. Initial total suspended solids (TSS) analysis was performed and the samples were either concentrated or diluted to 2500 mg/L mixed liquor suspended solids (MLSS), which is similar to JRWWTP’s operating condition, and settled in a 2L graduated cylinder while height measurements in cm centimeters were collected.

Additional evaluation of settling velocity was performed by determining intrinsic settling classes at discrete particle concentrations of ~150 mg/L MLSS. Settling velocity classes of < 1.5 m/hr for flocs, 1.5 – 3 m/hr for small aggregates, 3-9 m/hr for large aggregates, and > 9 m/hr for granules were established. The diluted mixed liquor initial and final TSS was measured after the sample was settled for either 20s, 1 min, 2 min, 3 min or 5 min. The percent of TSS removed during each time stamp was used to determine the settling velocity classes for each sample point.

Floc density for the aeration, underflow, and overflow were performed utilizing methodology developed Dammel and Schroeder, 1991 in which a media gradient solution is created by diluting Percoll, a silica colloid solution, with a weak salt solution so the ionic strength is similar to the secondary clarifier effluent. A density gradient from 1.05 to 1.13 g/ml is formed when centrifuged at high g-forces. The SIP solution was diluted to a target osmolality and centrifuged with density marker beads for 90 minutes at 17,000 x g. Upon completion, mixed liquor was added to a blank tube and centrifuged for 30 minutes at 400 g. The density of the mixed liquor was determined by comparing to the height of the density marker beads.

Shifts in microorganism populations were investigated in the aeration, underflow, and overflow mixed liquor with kinetic batch activity testing. All activity tests were performed at current wastewater temperatures maintained with a chiller, pH between 6.5 and 7.5 by bubbling carbon dioxide through a diffuser stone. Aerobic tests maintained dissolved oxygen (DO) between 2 and 4 mg/L with an air pump and diffuser stone. Anaerobic tests were thoroughly mixed on a stir plate and sparged with nitrogen gas. Samples were immediately filtered through 0.45μm cellulose membrane filters and analysis was performed with Test in Tubes (TNT) (HACH Company, Loveland Colorado). AOB and NOB rates were determined by dosing 2L of mixed liquor with 20 mg/L of NH\textsubscript{4}-N and 5 mg/L NO\textsubscript{2}-N and sampling every 15 minutes for NH\textsubscript{4}-N, NO\textsubscript{2}-N, and NO\textsubscript{3}-N analysis. PAO, dPAO, and GAO rates were determined by dosing 4L of mixed liquor with 10 mg/L PO\textsubscript{4}^{3-}-P at the start of a 120 minute aerobic phase, next 100 mg/L of COD was dosed for the 120 minute anaerobic phase, finally the mixed liquor was split into 2 2L batches one was
operated aerobically and the other was operated under anoxic conditions by dosing with 20 mg/L of NO$_3$-N. Samples were collected every 15 minutes and analyzed for orthophosphate (OP), sCOD, NH$_4$-N, NO$_2$-N, and NO$_3$-N.

RESULTS AND DISCUSSION

The hydraulic and mass splits were 80% overflow and 20% underflow during initial operation. However, after optimization the hydraulic split shifted to 95% overflow and 5% underflow (Figure 3). The mass split deviated from the hydraulic split indicating increased retainment of particles in the underflow which was verified with MLSS sample analysis. MLSS concentrations for the underflow increased to 40,000 mg/L while overflow and feed remained between 3000 and 5000 mg/L (Figure 4). Decreased volatile suspended solids (VSS) of 40% occurred in the underflow as more granule core material (GCM) was selected for with the hydrocyclone (Figure 5). Microscope analysis of the underflow indicates inorganic material was embedded within flocs (Figure 6)

![Figure 3: Changes on hydraulic and mass split upon continuous operation and optimization.](image)
Figure 4: Increased MLSS concentrations in underflow leading to improved mass split
Figure 5: Decreased underflow VSS% with increased retainment of granule core material

Figure 6: Inert materials embedded in flocs
ISV tests indicated increased velocities of > 20 m/hr for the underflow. Slight improvements of velocity in the aeration mixed liquor of > 2.0 m/hr occurred while the overflow settling velocity remained low typically < 1.0 m/hr indicating continued wasting of poor settling flocs (Figure 7).

![Graph showing increased settling velocity of underflow and aeration effluent](image)

Figure 7: Increased settling velocity of underflow and aeration effluent

Density for the overflow remained low at 1.03 and 1.04 g/mL (Figure 8). The underflow formed two distinct bands of which one had visible particles and with higher density values of 1.09 and 1.10 g/mL while the other was more comparable to well settling flocs with values of 1.07 to 1.08 g/mL. With continued hydrocyclone operation, the aeration effluent density increased indicating the potential for improved settleability. In addition, intrinsic settling class analysis further confirmed settling improvement as the aeration effluent increased settling rates from the < 0.6 m/hr class to the 1.5 to 9 m/hr settling classes.
JRWWTP operates an IFAS therefore AOB/NOB rates for underflow, overflow, and feed mixed liquor are dependent on the preference of the nitrifiers for media or bulk liquid. When nitrification is prominent in bulk liquid AOB/NOB rates are 0.5 to 1.5 mgNOx-N/gMLSS/hr and mgNO3-N/gMLSS/hr, respectively, for all fractions of the hydrocyclone indicating that washout of nitrifiers does not occur.

Ferric addition was altered in early 2016 to only manage the centrate load and coupled with maintaining biological phosphorus removal (Figure 9) reduction in total addition occurred when compared to previous years (Figure 10). Along with improvements to bioP with better management of SRT control plant settleability experienced periods of stability (Figure 12)
Figure 9: Phosphorus anaerobic release and aerobic/anoxic uptake rates showing stabilization of bioP.

Figure 10: Decrease in ferric addition with stabilization of bioP.
Figure 11: Periods of settleability stabilization improved bioP and SRT control
Conclusions:

Optimization of the hydrocyclone operation allowed for better selection of granular core material which leads to improved settleability. In addition, with stable bioP operation, an decrease in SVI stability occurred; however when bioP is unstable, a direct correlation with poor settleability can be seen along with increased ferric addition. This illustrates the potential to improve settleability as long as bioP can be maintained with continued optimization and operation of the hydrocyclones. Higher settling velocities were consistently measured in the underflow than the overflow indicating the dense particles are indeed being retained while lighter flocs are being wasted. Density measurement analysis showed higher densities in the underflow and a steady increase in the aeration effluent demonstrating the retention of denser particles in the entire system. AOB and NOB nitrification rates do not show the possibility of selective washout in the overflow. Further optimization of hydrocyclone operation, SRT control and stable bioP leading to increased settleability continues for the project which should provide the framework for the process of forming and maintaining aerobic granules.
References:


Mohlman F. The Sludge Index. Sewage Works Journal 1943, 6 (1) 119-122

