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# Gravimetric selection of activated sludge for settling properties improvement and granular sludge formation – full scale case study

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## ABSTRACT

With an increasing frequency of extreme weather events wastewater treatment plant operators face a need to increase plant hydraulic capacity while continuing to comply with effluent quality requirements. An economically attractive way to meet this challenge is to significantly improve secondary settling tank performance and therefore assure safe wet weather plant operation. The objective of this study was to evaluate gravimetric selection technology conducted in hydrocyclones as a way for improving activated sludge settling characteristics in continuous flow BNR with a long sludge retention time and assess its ability to form granular sludge. Long term operational data and sludge morphology monitoring data were analysed. A significant drop in sludge volume index (SVI) (to values under 50 ml/g) and increase in return activated sludge solids concentration (to values above 20 g/L) was observed. Hydrocyclone installation consistently, selectively retained denser, larger flocs in the system and after a start-up phase large granules begin to appear. Gravimetric selection did not prevent the seasonal filamentous biomass outgrowth and temperature drop at the beginning of winter resulted in rapid rise of SVI and SST sludge blanket height especially after heavy rain. Technology under study proved to be effective under certain process conditions but it needs further research to consistently maintain low SVI values throughout the whole year.

**Key words:** aerobic granular biomass, flocs size distribution, hydrocyclones

## HIGHLIGHTS

- Gravimetric selection in hydrocyclones improved seasonally activated sludge settling.
- Shear force in hydrocyclones did not prevent filamentous outgrowth.

## INTRODUCTION

One of the main hydraulic bottlenecks of activated sludge (AS) systems is efficiency of solid-liquid separation in secondary settling tanks (SSTs). In the event of wet weather inflow, SSTs with poorly settling sludge are prone to sludge blanket rise potentially leading to biomass washout. The number of factors influencing sludge settleability and compressibility is high (Jin *et al.* 2003) and for BNR systems with long sludge retention time (SRT), filamentous bulking is a frequent challenge (Gabb *et al.* 1991; Jenkins *et al.* 2004). Since some factors promoting filamentous outgrowth (interpreted as filamentous bacteria proliferation to the extent of interfering with sludge settling and compaction), such as temperature drop (Knoop & Kunst 1998), are beyond operators' control, novel solutions that help improve AS settling characteristics are in demand. One of most promising technologies for improving sludge sedimentation rate is aerobic granular biomass (AGB) (Nor Anuar *et al.* 2007). AGB has successfully been cultivated in full-scale sequencing batch reactor (SBR) systems (Pronk *et al.* 2015) using hydrodynamic shear force and feast-famine feeding regimes (Nancharaiah & Reddy 2018). Currently efforts are being made to achieve improve sludge settling characteristics in continuous flow systems by implementing two-zone sedimentation tank for selective retaining fast settling agglomerates and adding micropowder to induce bacterial attachment (Zou *et al.* 2018), introducing settling velocity selector and feed/famine conditions (Sun *et al.* 2019), seeding reactors with AGB and applying size-based selection (Corsino *et al.* 2016) or metabolic selection pressure while cultivating phosphate accumulation organisms (Devlin & Oleszkiewicz 2018). Successful laboratory scale continuous flow AGB systems required more than one granulation driver with settling velocity or particle size being the primary one. This led to the concept of using hydrocyclones – an external gravimetric selector previously used for full-scale deamonnification reactors (Klein *et al.* 2012; Wett *et al.* 2013) to selectively retain larger, denser particles.

The hydrocyclone is a simple mechanical device without moving parts that separates solid mixtures based on size and specific gravity. Thanks to its cono-cylindrical shape and tangential feed inlet it transforms feed pressure into centrifugal force (Bradley 2013). Particles entering a device spin in a high-velocity vortex and are separated based on terminal settling velocity. When fed with AS, a mixture of non-uniform floc densities and sizes, the hydrocyclone separates the feed into two fractions: underflow containing denser and/or larger flocs and overflow with lighter and/or smaller flocs. Hydrocyclone implementation in AS systems was the object of a few laboratory-scale and pilot research projects with a focus on sludge disintegration and releasing internal carbon sources (Liu *et al.* 2017; Xu *et al.* 2018, 2019). Xu *et al.* (2019) reported a slight improvement in sludge settling characteristics but that no AGB formation occurred while mean floc diameter decreased. Results of the successful full-scale hydrocyclone implementation in a AS system with low SRT was reported by Avila *et al.* (2021) were both biological and physical selection pressures were applied.

The objective of this study is to investigate potential for gravimetric selection technology conducted in a full-scale hydrocyclone installation to improve settling characteristic and achieve full or partial AGB development in a high-SRT BNR system, without changing biological selective pressure. Additionally, the hydrocyclone's ability to selectively remove filamentous bacteria by means of shear force was explored.

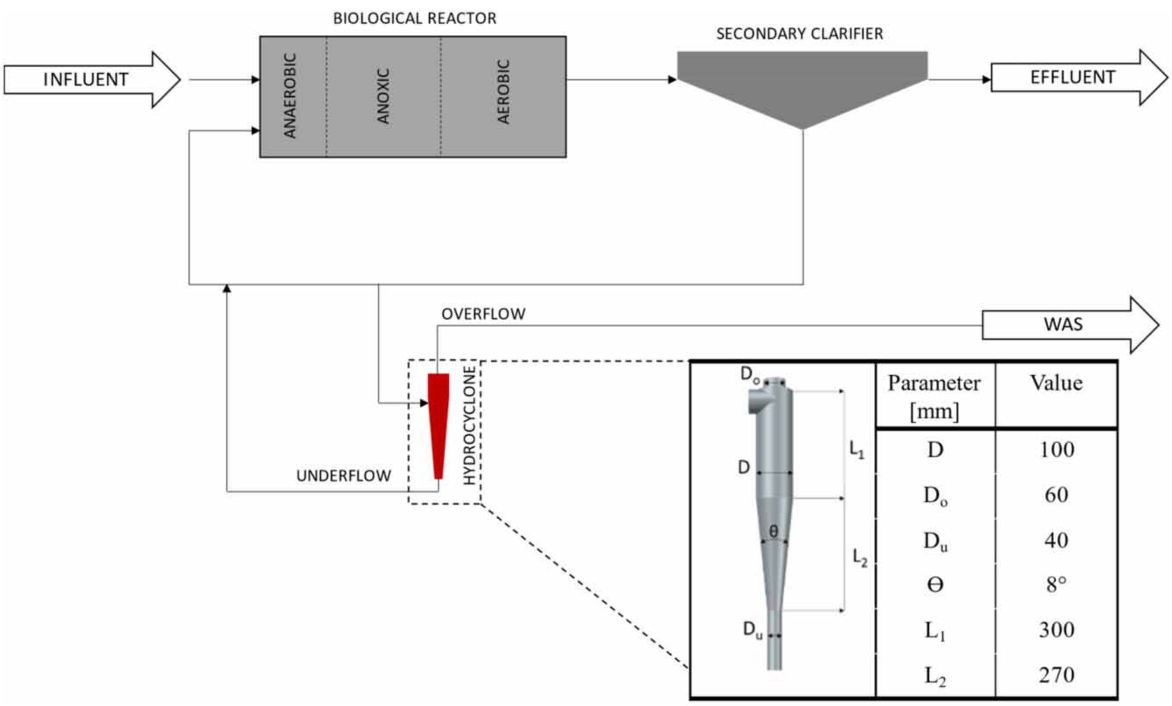
## MATERIAL AND METHODS

### System set-up

The system under study is an A2O AS WWTP with enhanced biological nutrient removal coupled with chemical phosphorus precipitation It treats on average 140,000 $m^3/d$ with a load of 1,050,000 P.E. A mean SRT of 25.9 $\pm$ 4.1 days was maintained. Biological treatment consists of five process lines (main operational parameters are presented in Table 1) with three independent sludge recirculation systems. Two process lines – experimental train – were equipped with gravimetric selection installation with an overall capacity of 5,400 $m^3/d$ placed in the return activated sludge (RAS) line. One process line – identical to experimental train – is referred to as the 'Reference train' and the other two due to difference in reactor configuration were not used in this study. The flow diagram of the experimental process train and hydrocyclone dimensions are presented in Figure 1. Approximately 1,400 $m^3/d$ was pumped through the hydrocyclone installation and separated into two fractions: retained underflow (UF) and overflow (OF), which is removed as waste activated sludge (WAS). Daily amount of WAS from each process line was set by process engineer.

**Table 1** | Operational parameters of a single process line

| Parameter | Unit | Value |
|---|---|---|
| SRT | d | 25.9 $\pm$ 4.1 |
| Inflow | $m^3/d$ | 29,300 $\pm$ 4,800 |
| MLSS (mixed liquor suspended solids) | $kg/m^3$ | 5.0 $\pm$ 0.5 |
| VSS/TSS | – | 70.3 $\pm$ 3.0 |
| MLR (mixed liquor recirculation) | $m^3/d$ | 77,200 $\pm$ 3,000 |
| RAS (recirculated activated sludge) | $m^3/d$ | 21,400 $\pm$ 11,600 |
| WAS (waste activated sludge) | $m^3/d$ | 1,120 $\pm$ 250 |
| Biological reactor volume | $m^3$ | 30,000 |
| %Anaerobic volume | % | 10 |
| %Anoxic volume | % | 40 |
| %Aerobic volume | % | 50 |
| Hydrocyclone feed | $m^3/d$ | 1,400 $\pm$ 310 |
| Underflow/feed hydraulic ratio | % | 21 $\pm$ 4 |




| Parameter [mm] | Value |
|---|---|
| D | 100 |
| $D_o$ | 60 |
| $D_u$ | 40 |
| Θ | 8° |
| $L_1$ | 300 |
| $L_2$ | 270 |

**Figure 1** | Flow diagram of activated sludge process with gravimetric selection technology.

Installation was fed sequentially following periodical WAS removal. When fed, constant inflow of 155 $m^3$/h and stable UF/Feed split ratio of 0.21 ± 0.04 in the hydrocyclone was maintained throughout the whole operation period under discussion.

### Analytical methods

The quality of the effluent 24 h-composite samples in the experimental process train and plant effluent was measured with standard photometric cuvette tests (Hach Lange GmbH) and DR6000 spectrophotometer (Hach Lange GmbH): total nitrogen (LCK 338), total phosphorus (LCK 350), chemical oxygen demand (LCK 114). The concentration of total suspended solids (TSS) was measured according to Standard Methods. The sludge volume index (SVI) after 30 minutes of settling ($SVI_{30}$) value was monitored according to APHA (2012) and used as a simple indicator of sludge settling characteristic throughout the whole trial period. The state of granulation was described by comparison of SVI after 5 minutes of settling (dSVI5) and 30 (dSVI30) minutes of settling sludge sample diluted to approximately 2 g/L (Etterer & Wilderer 2001). Floc size distribution was monitored using automated image analysis with a Malvern Morphologi G3 analyzer. Microscopic examination of the AS samples were performed according to Eikelboom (2000) and filamentous index (FI) was used as a parameter for quantification of filamentous microorganism population in the sludge.

## RESULTS AND DISCUSSION

### Effluent quality

Long-term operation of the hydrocyclone installation did not impact overall treatment efficiency. As presented in Figure 2, effluent quality – expressed as weekly averages – in the experimental process train did not deviate from plant effluent. The experimental process train effluent constitutes 40% of total plant capacity but since there is no significant, long-term difference between the two data sets in Figure 1 we assume that treatment process in both experimental and reference process train had comparable efficiency.

### Settling properties

Hydrocyclone installation start-up began in October 2019 and the first 60 weeks of operation data was analysed. The difference between $SVI_{30}$ variability in experimental vs. reference process train is presented in Figure 3. $SVI_{30}$ of the reference plant shows an increase when wastewater temperature drops below 19 °C, which is typical for this plant, and a decrease from a value of 190 mL/g to 120 mL/g between week 21 and 22 as a result of

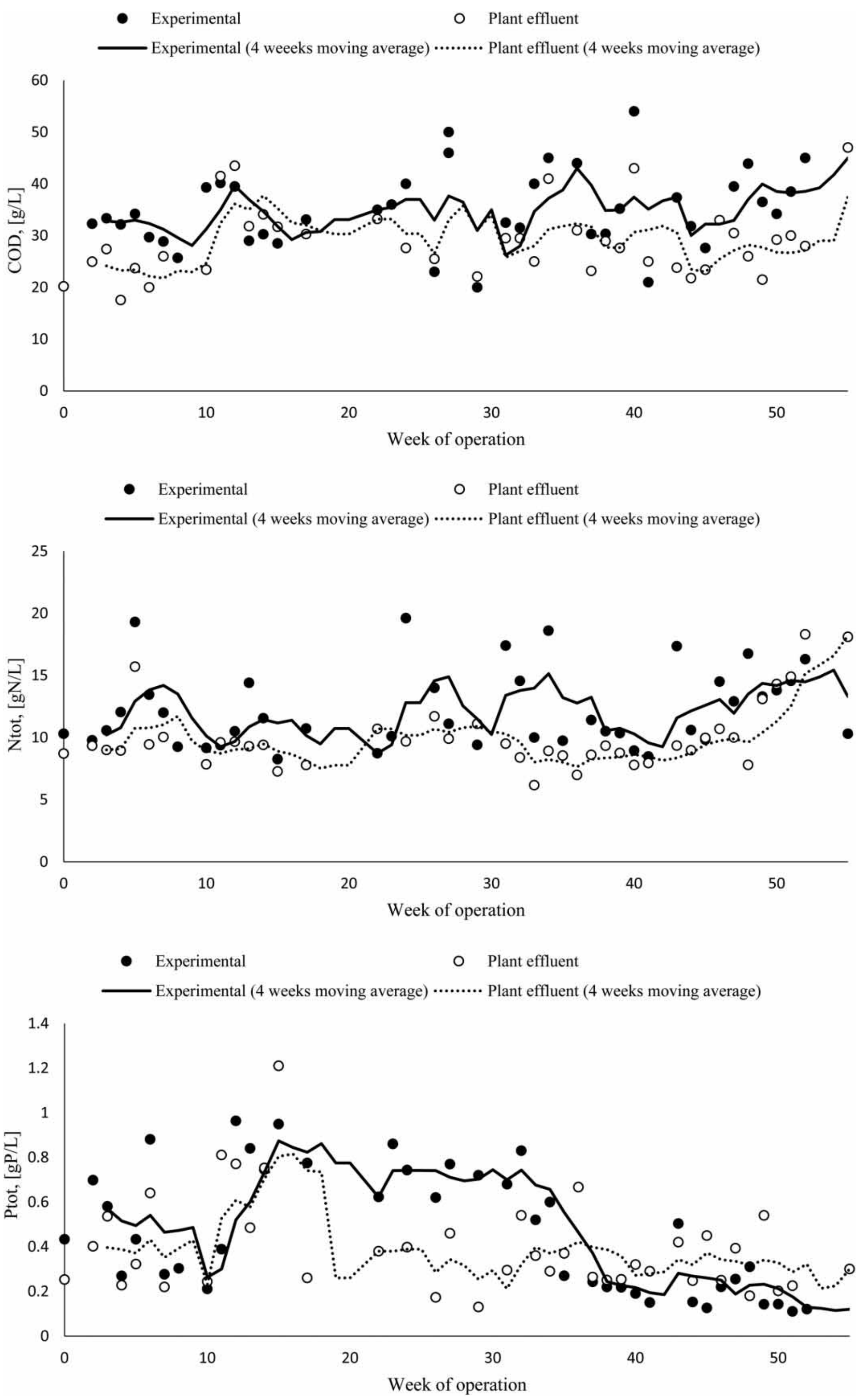



**Figure 2** | Effluent quality (COD, $N_{tot}$, $P_{tot}$) in experimental process train compared to plant effluent.

aluminium sulfate dosing. Gravimetric selection technology significantly reduced experimental $SVI_{30}$ values. The first quantifiable impact on performance was visible when a period equal to two SRTs or approximately 7 weeks had passed. The $SVI_{30}$ dropped noticeably in week 8 and then again in week 35. Settling characteristics were not stable and a sharp rise in SVI started in week 10 and 52. It is hypothesised that the reason behind this is seasonal filamentous outgrowth which happened concurrently in the reference process train. Noteworthy, despite dropping process temperature, installation start-up allowed for temporary improvement of settling properties.

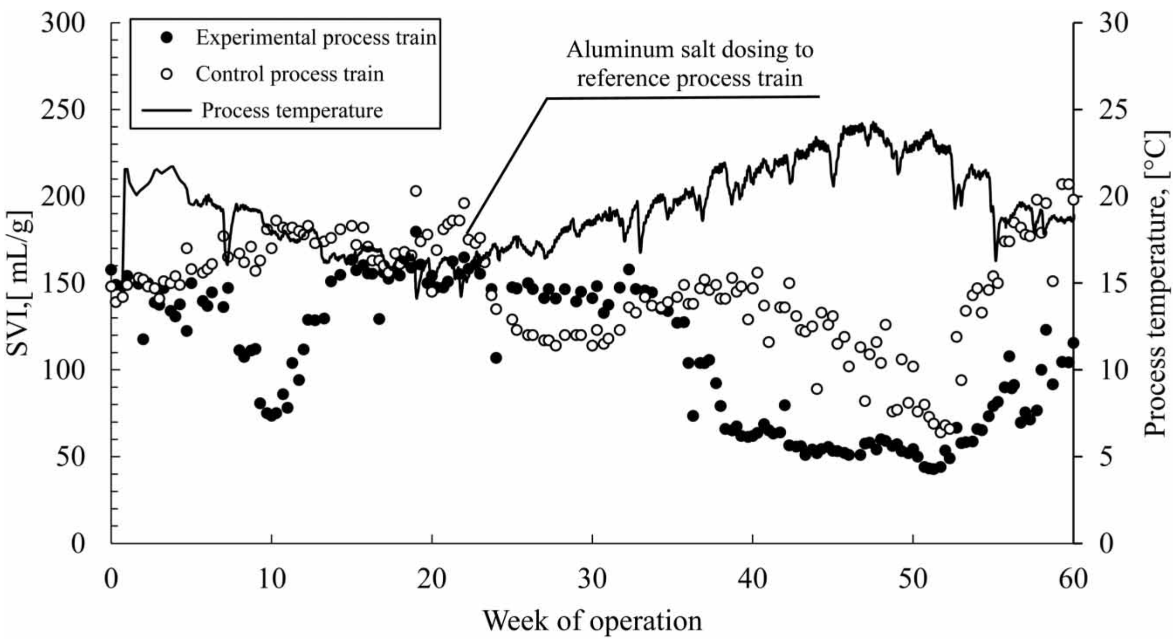



**Figure 3** | SVI30 variations in experimental and reference process train.

Improvement was not permanent and when SVI values rose to a similar SVI level as that of the reference train, the rise was of a much larger relative magnitude. The reason for the temporary improvement in SVI values during lower process temperature is a subject for further research since during the next cold season the SVI values rose and were stable during the whole season. (data not shown). In the experimental system, the poor settling period lasted till week 34 when a second rapid decrease in $SVI_{30}$ took place. $SVI_{30}$ values in the experimental process train dropped below those in the reference train, reached the level of 50 ml/g and remained stable during next 10 weeks. Based on the presented results, the beneficial, but seasonal effect of gravimetric selection technology on AS settling properties is evident. Between week 36 and 52 (warm season) the average $SVI_{30}$ values in in experimental and referenced AS were 61 mL/g and 115 mL/g, respectively, so that the value in the experimental system was 47% lower. Avila *et al.* (2021) reported 45% reduction in SVI in a system with much lower SRT, where AS selection pressure exerted by hydrocyclone is much higher. The data presented here show that a full-scale hydrocyclone installation in a high-SRT system can seasonally improve sludge settling characteristics characteristics to the same extent.

## Filamentous bacteria abundance

Table 2 presents FI values in sludge samples from experimental and reference process train. Since gravimetric selection conducted by hydrocyclones could potentially selectively remove filamentous microorganisms, additional microscopic analysis was done in WAS from experimental sludge samples. Although an average difference of 0.5 between experimental and reference AS can be noted, FI values for WAS removed from the system did not deviate from those in the AS, suggesting that the hydrocyclone did not physically separate filaments from the AS. It is worth noting that differences in FI between experimental and reference train should not be the sole indicator of different settling properties. As can be seen in Figure 3 and Table 2 when SVI in experimental train

**Table 2** | FI values in experimental and reference process trains throughout first 15 weeks of operation

| | Experimental | | Reference |
|---|---|---|---|
| **Week of operation** | **AS** | **WAS** | **AS** |
| 3 | 2.0 | 1.5 | – |
| 7 | 3.0 | 3.0 | 3.5 |
| 11 | 2.0 | 2.0 | 2.0 |
| 15 | 2.0 | 2.0 | 3.0 |

deviated from reference one by week 11, FI values in all three samples were the same. Other factors such as flocs size and density play a major role in sludge settling characteristics, but would not be captured by FI From the results given it can be concluded that filamentous bacteria cannot, in this system setup and operating conditions, be selectively removed by a hydrocyclone. It is hypothesised that filamentous microorganisms in AS has a twofold effect when improvement of settling properties by means of gravimetric selection is considered. Low levels of filaments in activated sludge is believed to act as a backbone to the floc structure. As stated by Burger *et al.* (2017) filament abundance increases the floc strength factor and therefore its resistance to shear stress. This would suggest that flocs with a certain filament content may be less susceptible to shear and centrifugal forces in hydrocyclone and therefore are more likely to form larger, stable flocs that might turn into granules. On the other hand, since hydrocyclone could not selectively remove filaments, this technology did not control filamentous outgrowth and its destructive effect on sludge settling properties when they start to protrude from the floc (Wágner *et al.* 2015).

## Sludge granulation

As typical AS flocs switch to granule form $SVI_5$ values decrease and approach $SVI_{30}$ values. Figure 4 presents $dSVI_5$ and $dSVI_{30}$ data in experimental train. It could be seen that although during the whole analysed period that $dSVI_5$ values were continuously higher than $dSVI_{30}$ (80 ml/g between 18 and 22 week), after 36 weeks' difference between them was reduced to 30 ml/g.

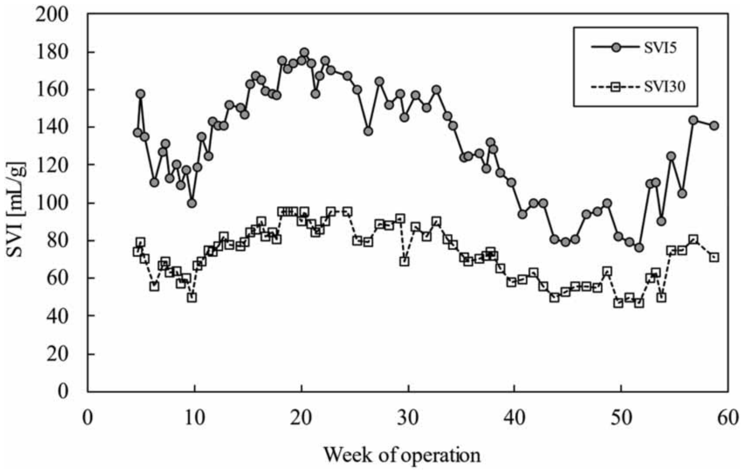



**Figure 4** | Sludge volume index after 5 (SVI5) and 30 (SVI30) minutes in experimental process train.

As seen in Figure 5 floc size distribution shifted. Floc median diameter increased from 200 μm in week 20 to 400 μm in week 40 when $SVI_{30}$ dropped to 50 ml/g. Aggregates larger than 500 μm constituted only 5% of all flocs volume in week 20 but increased to 30 and 25% in week 40 and 60, respectively. In addition, a change

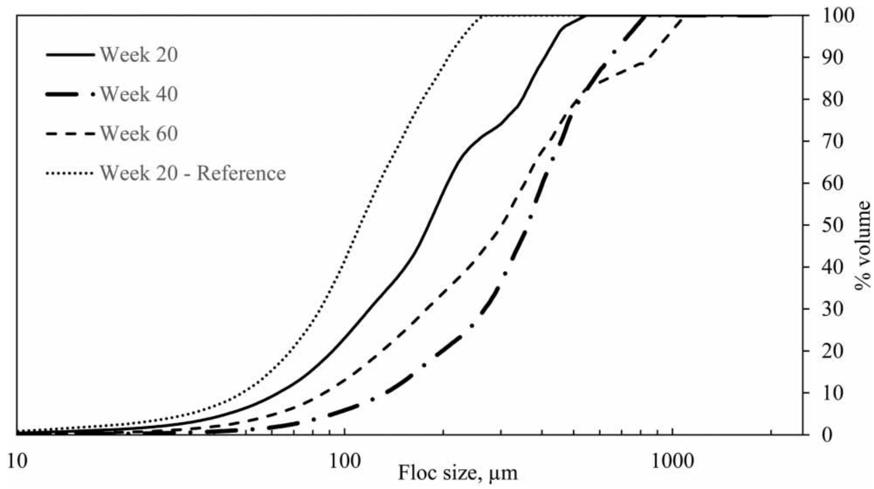



**Figure 5** | Floc size distribution shift in experimental process train.

in sludge morphology is confirmed by the more frequent occurrence of granule-like aggregates with diameter exceeding 1,000 μm. Sludge granulation was not complete: in week 40, with the lowest $SVI_{30}$ values, 50% of all flocs by volume remained smaller than 400 μm. It is critical to note that from an operator's point of view full granulation in a continuous flow system might not be desirable. Absence of smaller flocs in SST, that form continuous matrix during settling, trapping dispersed biomass, might result in elevated effluent TSS concentrations (Pronk *et al.* 2015; Avila *et al.* 2021).

Results of implementing gravimetric selection of recycled activated sludge presented in this full-scale case study as well as that by Avila *et al.* (2021) contradict findings of a lab-scale experiment from Xu *et al.* (2019) were hydrocyclone operation decreased average floc size and no granules occurred. Reasons behind that might be different time-scale, operation condition such as overflow/feed ratio or lack of mineral precipitates that in full scale demonstration might have acts as granule seed. All of the above prove that exact mechanism behind hydrocyclone AS selection is not yet fully understood and its implementation in different wastewater treatment systems might have unknown outcomes.

## CONCLUSIONS

A full-scale implementation of activated sludge gravimetric selection technology was demonstrated at large BNR WWTP operated at high SRT with an aim to improve SST performance by changing sludge morphology. A hydrocyclones installation has been in operation since October 2019 and 60 weeks of operational data from both experimental and reference process trains were analysed. The evaluation of the effects of the technology on activated sludge morphology, settling properties and an overall plant operation lead to the following conclusions:

- The start-up phase lasted app. two SRTs when after the initial phase quick improvement in settling characteristics occurred with an average decrease in SVI of 14 ml/g every week.
- Shear forces acting in hydrocyclones did not prevent filamentous growth during the cold season.
- Aside from the cold season, gravimetric selection technology proved to be able to significantly improve settling characteristics of AS and increase the hydraulic capacity of the SST and therefore assure safe wet-weather operation.
- Long-term hydrocyclone operation resulted in a clear change in sludge morphology. Sludge in the experimental train had a significantly higher frequency in granule occurrence.

## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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