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Development of Naval Controlling Loops for Primary Sludge Thickening Process at SNJ Wastewater Treatment Plant

Master's Thesis

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Abstract

The solid concentration of primary sludge is increased by thickening process of the wastewater treatment plant (WWTP). At SNJ WWTP, rotary drum thickener is used to thicken primary sludge and expected to obtain 5 ±1 % (Total Solids) TS from effluent. Therefore, primary objective of this study is to optimize the thickening process in order to obtain effluent TS 5 ±1 %.

Laboratory scale experiments have been conducted on eight different days to investigate effect of the flocculent dosage (g flocculent/ kg TS) on flocculation and dewaterability. Time to Filter (TTF) test represented dewaterability and turbidity of filtrate test represented the effectiveness of flocculation of primary sludge. The sludge characteristics (TS, TSS, turbidity of supernatant, alkalinity, conductivity and VFA) changed each day. Hence, similar TTF or turbidity of filtrate values were not observed at constant flocculent dosage. Among the characteristics of sludge, turbidity of supernatant represented colloidal solids of the primary sludge which influenced the dewaterability and flocculation variation mostly. Consistent dewaterability was not observed even though primary sludge was mixed with secondary sludge.

The effect of operational parameters (rotational speed of thickener, backwash mechanism, mixing speed of flocculator mixer and flocculent dosage) on the thickening process at SNJ WWTP were investigated through full-scale experiments. Optimum rotational speed of thickener was identified as 4.8 rpm. The backwashing system should be operated in minimum 12 seconds to clean the whole drum filter at a rotational speed of 4.8 rpm with a maximum pause period of 1 minute between two backwash cycles. The turbulence was created by mixer of flocculator reactor required to obtain better dewaterability when influent TS was lower than 0.8%. However, better dewaterability could be obtained without using the mixer of the flocculator when influent TS was greater than 1%. Flocculent dosage was identified as the main manipulated variable of thickening process to obtain effluent TS 5 ± 1 %. Out of the five different controlling loops developed, controlling loop 3 and loop 4 were the most reliable to obtain effluent TS 5 ±1 % and economically viable controlling methods for primary sludge thickening process at SNJ WWTP. These were developed by considering influent TS and influent flowrate as feedforward parameters and turbidity of filtrate and flowrate of filtrate as feedback parameters for controlling loop 3 and loop 4 respectively.

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Abbreviations

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CV	Coefficient of Variation
DAF	Dissolved Air Floatation
EU	European Union
FENP	Iron Nanoparticles
GBT	Gravity Belt Thickener
HRT	Hydraulic Retention Time
OM	Organic Matter
PE	Population Equivalent
RDF	Rotary Drum Filter
RDT	Rotary Drum Thickener
RPM	Rounds Per Minute
SNJ	*Sentralrenseanlegg Nord-Jæren*
SRT	Solids retention Time
TS	Total Solids
TSS	Total Suspended Solids
TTF	Time To Filter
VFA	Volatile Fatty Acid
WAS	Waste Activated Sludge
WWTP	Wastewater Treatment Plant

1. Introduction

Wastewater treatment technologies have been developed in order to protect natural environment and enhance resource recovery. Wastewater treatment plant (WWTP) can consist of preliminary, primary, secondary and tertiary treatment stages before discharging effluent in to the environment. Preliminary treatment technologies remove large objects, rags, grits oil and fats from wastewater. Therefore, such technologies protect moving instrument such as pump. Effluent of preliminary treatment is transferred to the primary treatment stage. In here, suspended solids are removed and usually treated further by methods such as thickening, anaerobic digestion, dewatering, etc. (Hopcroft, 2014).

The primary objective of the thickening process is to increase the solid fraction by removing significant amounts of liquid from the sludge. Concentrated sludge is beneficial to the downstream processes such as digestion, dewatering, drying, and disposal. Concentrated sludge has a lower volume. Hence, chemicals, energy requirement and capacity of downstream processes are significantly reduced (Tchobanoglous, et al., 2014).Therefore, sludge treatment process is highly depended on a stable thickening process. Gravity sedimentation, gravity belt thickening, centrifugal, dissolved air flotation and rotary drum thickening are widely used sludge thickening methods in WWTPs.

The regional wastewater treatment plant of Nord-Jæren (SNJ) is collecting primary sludge through rotary drum filters and is thickened by rotating drum thickener before pumping to the buffer tank of mesophilic anaerobic digester.

It is important to obtain effluent expected solid concentration (5% TS) from thickener to overcome operational consequences at SNJ WWTP. Too thick sludge(6%>TS) has a lower flowing property which is not possible to pump from sludge holding tank to the anaerobic digesters. Table 1.1 shows solids retention time (SRT) of digesters at SNJ WTWP when thickened primary sludge TS varied from 2 to 7%. Too thin sludge (4% < TS) causes to reduce SRT of the anaerobic digesters significantly. As a result, overload of primary sludge lowered pH in the digesters and stop biogas production.

In 1992, SNJ WWTP was built with chemical treatment methods and reconstructed in 2018 with secondary and mechanical treatment methods. Rotary drum filters at SNJ WWTP produce inhomogeneous primary sludge compared to the conventional primary treatment methods.

Therefore, thickening of primary sludge is more challengeable and required strict process controlling methods to obtain effluent TS of 5%.

Table 1.1 *SRT of digester at SNJ WWP (Appendix 1.1)*

Thickened Primary Sludge TS (%)	**SRT of Digester (d)**
2	9.5
3	12.2
4	14.3
5	15.9
6	17.2
7	18.28

Detail literature review has been conducted to identify research gap and objectives of this study. The main objective of this study was to optimize thickening operation by developing naval controlling loop for thickening process. To achieve objectives, methodology was developed and experiments were conducted as laboratory scale and full-scale experiments. Effects of sludge characteristics to the flocculation and dewaterability were identified through laboratory scale testing while full-scale testing investigated effect of operational parameters of thickener (flocculent dosage, rotational speed of thickener, backwash mechanism, and mixing speed of flocculation reactor) to the effluent solid concentration.

"Development of naval controlling loop for primary sludge thickening process at SNJ WWTP" thesis report is built with eight chapters.

1. Introduction;
2. Literature Review and Theoretical Background;
3. Materials and Methods;
4. Results and Discussions;
5. Error analysis;
6. Conclusions;
7. Recommendations;
8. Reference

2. Literature Review and Theoretical Background

This chapter explains theoretical background behind wastewater characteristics, primary treatment and sludge thickening methods. Also, an overview of SNJ WWTP is presented and its primary treatment and sludge thickening process are described in detail. Previous studies have been done on corresponding thickening process and previously used controlling loops for primary sludge thickening process at SNJ WWTP are evaluated in order to identify research gaps within the thickening process and objectives of this study.

2.1 Wastewater Characteristics

Municipal wastewater contains variety of constituents that originate from different sources such as domestic and industrial discharge, agricultural, mineral erosion and surface runoff. Therefore, characterization of wastewater in terms of its physical, chemical and biological parameters is essential to design and optimize of wastewater treatment process. Among them, physical and chemical characteristics of wastewater such as solids, turbidity, pH, conductivity, and alkalinity provide information with respect to optimization of physical and chemical treatment processes (Tchobanoglous et al., 2014).

2.1.1 Solids

Wastewater sample without coarse material is used to determine solids. It can be classified according to their size and settleability. Figure 2.1 shows general particle size distribution in wastewater. Compounds present in wastewater can be considered as dissolved solids (diameter $< 10^{-3}$ µm), colloidal solids (10^{-3} µm < diameter<1 µm) and suspended solids (diameter >1 µm). Particulate term is used to describe organic matter present in the suspended solids. Recently, micro and ultrafiltration is used to further separate colloidal and dissolved solids into much narrow ranges (Dulekgurgen et al., 2006; Ravndal et al., 2018).

Settleable solids are able to settle at the bottom of the Imhoff cone under the influence of gravity in a period of 1 hour. Usually, 60% of suspended solids in municipal wastewater is considered as settleable solids(Tchobanoglous et al., 2014). The remaining suspended solid fraction, colloidal solids, and dissolved solids represent the non-settled solids.

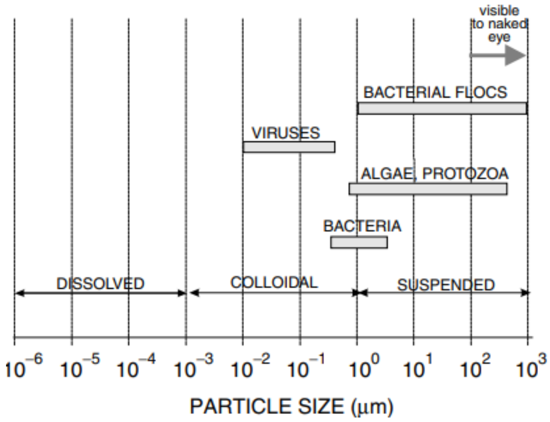


Figure 2.1 *Distribution of solids according to the size (Sperling, 2007)*

2.1.2 Turbidity

Turbidity of wastewater refers to the light scattering properties of a sample. Turbidity response increases when intensity of scattered light is increased. The light scattering property depends on the size, shape and refractive index of the particles containing in a wastewater sample. Particle diameters between 0.1 -1 µm produce highest turbidity response. No significant turbidity response produced from particles size lower than 0.1 µm and particles diameter higher than 1 µm can produce progressively lower turbidity response (Tarleton, 2014). Some particles absorb incident light, hence, there is no general relationship between suspended solids in wastewater and turbidity. Turbidity of wastewater is not an accurate measurement compared to the gravimetric solid measurements; however, it is a reliable and convenient parameter for real time process control.

2.1.3 pH, Conductivity, and Alkalinity

pH expresses as concentration of hydrogen ion in a solution. Alkalinity is defined as ability to resist a pH change caused by the addition of acid or base. Hydroxides, carbonates, and bicarbonate ions resulted in producing alkalinity in wastewater.(Woodard et al., 2005). Those ions combined to the element such as magnesium, calcium, and sodium. Conductivity refers to the ion concentration in wastewater. Conductivity can be used to determine total dissolved solids and ionic strength of the wastewater.

2.2 Wastewater Characteristics in Scandinavia

Wastewater characteristics may vary from country to country and from plant to plant. Ødegaard (1999) reported wastewater characteristics of Scandinavian plants (Table 2.1). According to data, Sweden and Finland were found to be more concentrated with suspended solids compared to the Norwegian wastewater. As well as, effluent of Finland and Sweden WWTPs are discharged to the areas much more vulnerable compared to the Norwegian WWTPs. Due to that, more comprehensive treatment process is required in Finland and Sweden.

Table 2.1 *Average suspended solids and Total COD values in raw wastewater from Scandinavian WWTPs(± standard error) (Ødegaard, 1999)*

Country	**Number of Plants**	**Suspended Solids (mg L^{-1})**	**Total COD (mg L^{-1})**
Sweden	17	243±87	477±123
Finland	12	378±144	559±161
Norway	7	143±39	233±69

Figure 2.2 shows each plant suspended solids COD fraction with respect to the total COD of the raw wastewater. The fraction of suspended organic matter (particle size>1 µm) of each country was high and around 70% of the total COD even though total COD was varied from country to country. Suspended organic fraction did not include colloidal COD fraction. Usually colloidal COD fraction represents 10-15% of the total COD. The remaining fraction 15-20% is soluble COD (Ødegaard, 2000, 1998).

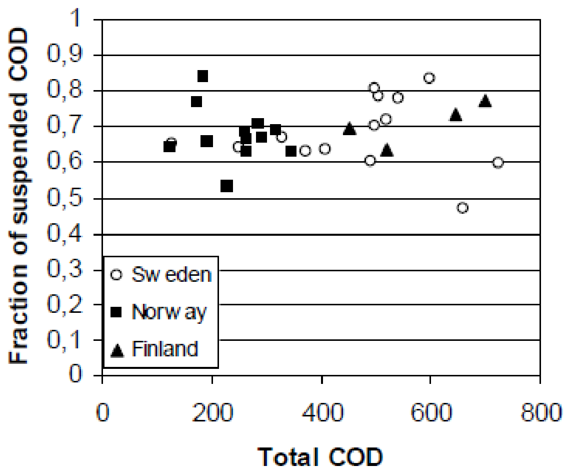


Figure 2.2 *Fraction of suspended COD and total COD in Scandinavian WWTPs(Ødegaard, 1999)*

Soluble organic matter of the raw wastewater is fluctuated by aerobic/anaerobic condition prevailing in the sewers network. The sewers are laid with a low inclination and the pipelines are filled in most occasions. Hence, anaerobic conditions can occur. Such condition causes hydrolysis of particulate matter into soluble organic matters, i.e. volatile fatty acid (VFA). On contrary, when sewers are laid with steep inclination, aerobic conditions occurred due to the turbulence of wastewater flow and soluble, easily biodegradable organic matter is turned into the particulate matter. This will be influenced to increase particulate/colloidal fraction in raw wastewater. Usually, soluble COD of Norwegian wastewater is well below 100 mg L^{-1} as well as non- biodegradable soluble COD in there is around 30-40 mg L^{-1}. Oxygen rich environment in Norwegian wastewater is causing to reduce soluble COD concentration. (Ødegaard, 1998)

Ravndal et al. (2018) evaluated physical and chemical components in raw wastewater of the SNJ WWTP in Norway. Table 2.2 presents COD and inert concentration in different size distribution such as particulate (>0.65 µm), colloidal (1000 kDa -0.65 µm), polymeric (1-1000 kDa), and oligomeric and monomeric (<1 kDa). According to this study, the soluble COD and non- biodegradable soluble COD of SNJ wastewater are higher than average respective COD of Norwegian wastewater.

Table 2.2 *Concentration of total COD and inert COD in raw wastewater, TSS filtrate, and all size fractions from SNJ raw wastewater (±standard error)* (*Ravndal* et a*l., 2018)*

Fraction	**COD (mg L^{-1})**	**Inert (mg COD L^{-1})**
Raw WW	690± 30	191± 10
TSS filtrate	262± 10	121± 6
>1mm	139± 5	11±3
100 µm -1mm	27 ±4	5.6 ± 0.8
25-100 µm	37.2± 0.8	5.3 ± 0.5
0.65-25 µm	101.6 ± 0.9	2.5 ± 0.5
0.1-0.65 µm	0.64 ± 0.02	0.06 ± 0.04
1000 kDa-0.1 µm	0.2±0.02	0.035 ± 0.003
100-1000 kDa	0.382 ±0.009	0
10-100 kDa	2.6 ± 0.3	0.71 ± 0.09
1-10 kDa	6.36± 0.06	1.2 ± 0.2
<1 kDa	363± 0.06	233± 6

Also, Figure 2.3 shows percentage of COD and chemical composition in SNJ WWTP raw wastewater. High COD concentration was found in particular (44 ± 2%), and oligomeric and monomeric fractions (53 ± 2%) compared to the polymeric and colloidal size fractions. This was due to the degradation or coagulation and flocculation of colloidal and polymeric matters in the sewer system. However, high inert concentration in colloidal and polymeric fraction suggested that significant biodegradation occurred in the sewer system.

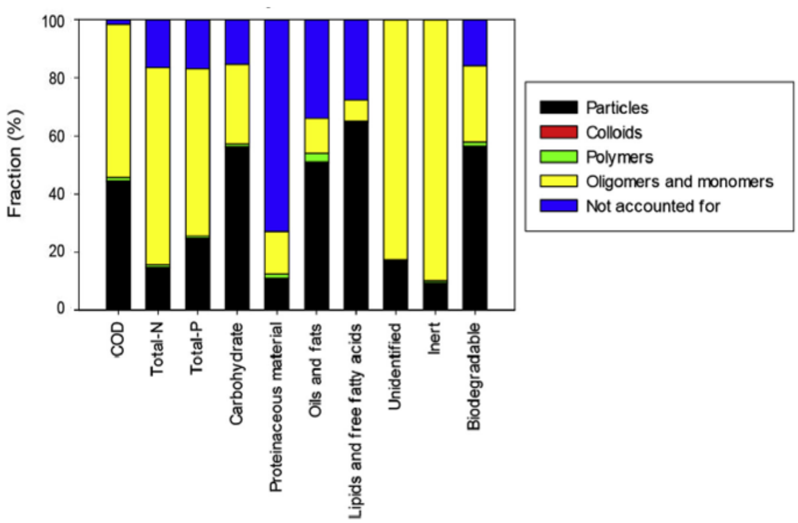


Figure 2.3 *Size distribution of organic matter in particulate (>0.65 mm), colloidal (1000 kD - 0.65 mm), polymeric (1-1000 kDa) and oligomers and monomers (<1 kDa) size ranges in SNJ raw wastewater* (Ravndal et al., 2018)

2.3 Primary Treatment Methods

The objective of primary treatment is the removal of suspended solids. This is done after coarse solids, grit, sand, and fat has been removed in preliminary treatment process. Sedimentation, floatation, micro screening and filtration methods have been developed as primary treatment methods (Tchobanoglous et al., 2014).

2.3.1 Primary Sedimentation

Primary sedimentation is governed by the gravitational settling of particles. Hence, 50- 70% of total suspended solids (TSS) and 25 to 40% of the biochemical oxygen demand (BOD) is removed through primary sedimentation tank (Tchobanoglous et al., 2014). Chemical enhanced primary sedimentation is an advanced method, where chemicals such as ferric chloride, aluminum sulfate are used to improve the particles settling by forming dense particles (Bezirgiannidis et al., 2019). As a result, volume and energy requirement for subsequent processes (biological reactors) are reduced (Giorgi et al., 2018). On the other hand, necessary nutrients and organic compounds can be removed from primary sedimentation, which are essential for biological nutrient removal and biological phosphate removal processes. (Amerlinck, 2015). Moreover, Cao and Pawlowski (2012) discovered primary sludge produced from primary sedimentation has a higher biogas potential (of 61.0 m^3 biogas produced from 100 kg of primary sludge) compared to the waste activated sludge (24.4 m^3 produced from 100 kg of waste activated sludge).

2.3.2 Floatation

Floatation is an alternative primary treatment method whereby fine air bubbles are introduced in to the liquid phase. Introduced air bubbles get attached to the particles in slurry and rise to the liquid surface (Tchobanoglous et al., 2014). There are two types of floatation, namely dissolved air floatation (DAF) and depressed air floatation. DAF has been successfully used in different applications such as removing algae and humic substance in drinking water, sludge thickening, and removing heavy metals from gold cyanide leaching solution other than the primary treatment method. (Kordmostafapour et al., 2006). However, DAF has been widely used in municipal wastewater treatment plants compared to the depressed air floatation. (Tchobanoglous et al., 2014). DAF has an ability to remove slowly settling particles. Therefore, DAF removes higher percentage of particles at a lower retention time compared to the traditional primary sedimentation tank. (Amerlinck, 2015; Atamaleki et al., 2020). However, energy requirement is much higher due to the air bubbles formation. Chemicals additives such as ferric salts or activated silica can be added to the floatation process in order to improve surface or structure of the particles that can easily absorb into the air bubbles. (Tchobanoglous et al., 2014).

2.3.3 Microscreen

Microscreen filters are an alternative method for primary sedimentation, especially, when space is limited. Lema and Suraz (2017) reported microscreen only occupies one-tenth of the primary clarifier footprint. The pore size of microscreen filter range from 10µm -1000µm and its filter medium can be made of woven polyester, stainless steel, and synthetic materials. (Lema and Suarez, 2017; Väänänen, 2017). Particles sizes lager than pore size of filter medium is effectively separated. As a result, effective pore size of filter medium is reduced and smaller particles started retaining on the filter medium. The solids retaining on the filter medium are called as filter cake. It reduces effective pore size and enhances filtration. On the other hand it would influence to reduce permeability of the filter medium (Ljunggren, 2006). Therefore, it is necessary to control filter cake thickness for optimum filtration. Commercially available microscreen configurations are rotary belt filterers, rotary drum filters, and rotary disc filters (Lema and Suarez, 2017).

2.3.3.1 Rotating Drum Filter

The Rotating drum is covered by a filter medium. During the operation, particles retaining on the filter medium and water level inside the drum is increased until backwashing is started. Effectiveness of drum filter depends on factors such as mesh pore size, mesh number, particle distribution, particle concentration, and hydraulic load (Xiao et al., 2019). Figure 2.4 illustrates relationship between mesh number and TSS removal efficiency.

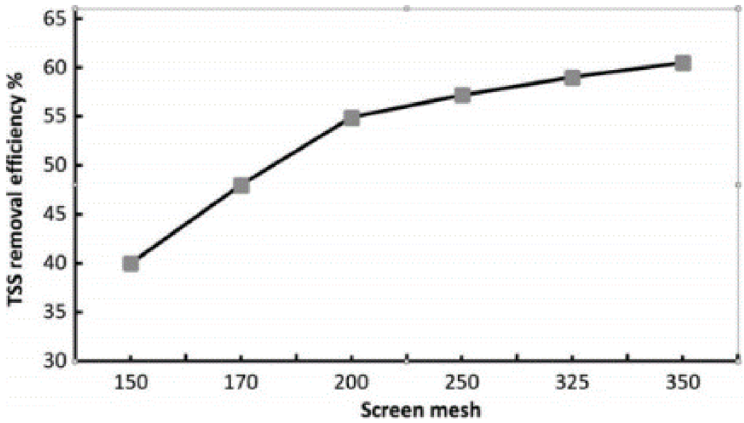


Figure 2.4 *The relationship between filter mesh number and TSS removal efficiency (Xiao et al. 2019)*

TSS removal efficiency increases from mesh number 150 to 200 due to the reduction in aperture size. However, higher backwash frequency is needed for higher mesh number. Filtration performance of drum filter can be improved with polymer condition. Väänänen, Cimbritz and la Cour Jansen, (2016) reported rotating drum filter with 100 µm pore size filter has removed 50% TSS from municipal wastewater without chemical pre-treatments. However, filtration performance was increased more than 95% by combining with polymer condition and drum filter. Rotating drum filter produces 0.5-1% sludge after primary treatment (Väänänen 2017).

2.4 Types of Thickeners

The objective of thickening process is to increase solid content of sludge by removing fraction of water content. Sludge characteristic, energy consumption of thickener, and treatment objectives are influenced for selecting specific type of thickener. Gravity thickener, rotary drum thickener (RDT), and gravity belt thickener (GBT) are widely used in the industry and are discussed in below section (Tchobanoglous et al., 2014).

2.4.1 Gravity Thickener

Gravity thickeners are widely used in industry due to its simple operating principle. That principle is similar to the sedimentation tank. Gravity thickeners are used to thicken primary, mixed and activated sludge. However, primary sludge is thickened to a solid concentration around 3-10 % while 3-6% for mixed sludge. Hydraulic loading needs to be controlled in order to perform thickener effectively. High hydraulic loading causes increased solid concentration in effluent while low hydraulic loading causes to produce septic and floating sludge (Tchobanoglous et al., 2014). Low maintenance and energy cost, sludge storage ability, and low operator attention are advantages of gravity thickener other than simplicity. However, disadvantages of gravity thickener such as higher footprint, less thickening capability compare to other methods, and septicity limit installing of gravity thickener (Bajpai, 2015).

2.4.2 Gravity Belt Thickeners (GBTs)

GBT is suitable for sludge concentration less than 2 %. It has been used for thickening sludge such as aerobic sludge, anaerobic sludge, and activated sludge. Therefore, this method is commonly used for waste activated sludge thickening application. Polymer addition is required before sludge feeding to the rotating belt. After polymer addition, it has an ability to produce a maximum of 4 to 7 % of thickening sludge (Tchobanoglous et al. 2014). The controlling parameters of GBT are polymer dosage, feed rate and belt speed. The energy cost of GBT is lower than the energy cost of RDT while polymer cost of GBT is slightly higher than RDT (Gabb et al., 1998).   GBT also requires odor controlling system because it is open to the surrounding (Dentel and Qi, 2014)

2.4.3 Rotary Drum Thickeners (RDTs)

RDT has capability to produce 5-9 % of solids and 95% solid recoverability when polymer condition is implemented prior to the thickener. Flocculated solids are introduced at inlet of the drum, where series of rotating sieves are attached to the drum (Figure 2.5). Flocculated solids are separated from water through rotating sieves. RDT is commonly used in WAS thickening applications(Dentel and Qi, 2014). RDT requires a lower space compared to the gravity thickening methods, however operation of thickener is more complexed. Therefore, it is essential to have an effective controlling system or require more attention to the variables of sludge thickening process.

The thickening process can be optimized through controlling variables such as sludge feed rate, type of polymer, dosage of polymer, Agitator velocity in the flocculation tank, rotation speed of the drum, drum cleaning interval and drum inclination (López et al., 2015).

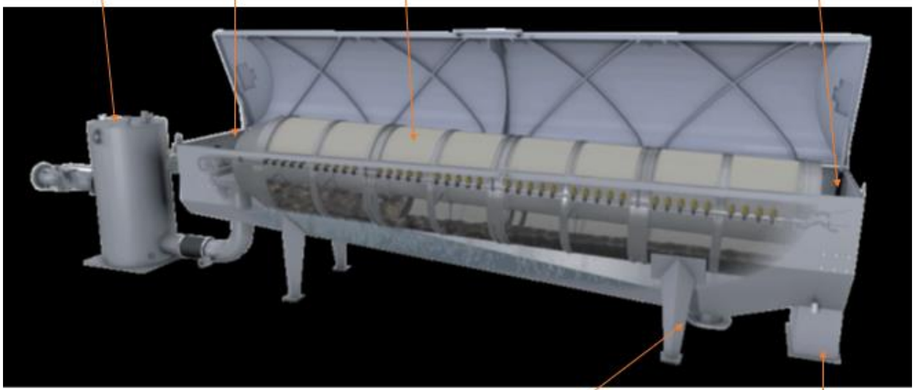
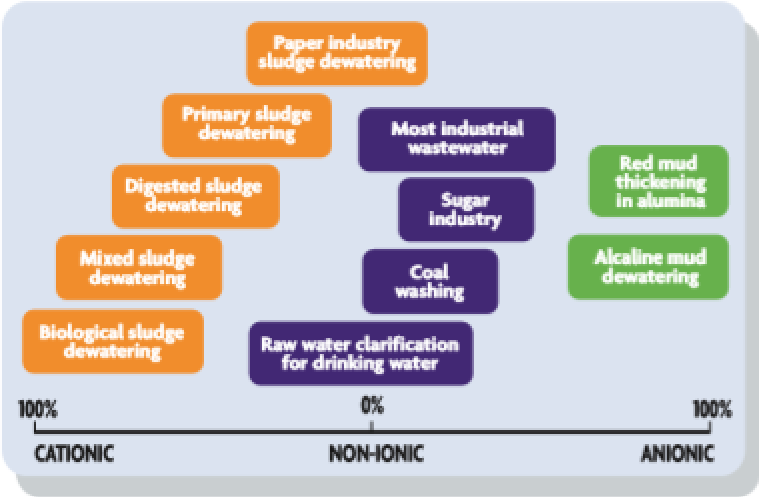


Figure 2.5 *Rotary drum thickener schematic diagram(Ydstebø and Egeland, 2019a)*

2.5 Flocculation

Chemical treatment methods such as coagulation and flocculation are essential to remove colloidal solids in wastewater. In coagulation, chemicals (coagulants) are added to destabilize the particles and facilitate to form flocs through perikinetic flocculation (Bratby, 2016). However, in flocculation, chemicals (flocculents) are added to form flocs through both perikinetic and orthokinetic flocculation. Perikinetic flocculation and orthokinetic flocculation refer to the flocculation of colloidal particles due to Brownian motion and induced velocity gradian respectively (Tchobanoglous et al., 2014). Flocculents are classified according to their charge, which are anionic, cationic, and nonionic. The flocculation process is explained by bridging model. According to the model, flocculents with their long chain of monomers and ionic charge adsorb the particles in the wastewater on their chain and produce flocs (Tuan et al., 2012).

Charge density of the sludge is determined for selecting flocculent. Charge density of the municipal sludge is caused by the organic matter (OM) content. OM is generally charged negatively. Therefore, low cationic flocculent is required for the best flocculation of municipal sludge(Floerder, 2014). Figure 2.6 shows the required flocculent charge for different type of sludge. CC FLOC D 6144K cationic flocculent is used for flocculating primary and secondary sludge at SNJ WWTP.



.***Figure 2.6*** *Suitable flocculent charge for different sludge(Castillo, 2018)*

2.6 Factors Affecting Thickening Process

Sludge conditioning process enhances the solid-liquid separation by forming large flocs. Due to that, flocculation step is combined prior to the primary sludge thickening process. Influent sludge characteristics and operational parameters of thickener impact the thickening performance. Overall, quality of thicken sludge is depended on thickening and flocculation performance.

2.6.1 Solids Content

Particle distribution in sludge influenced the dewaterability of sludge. Smaller particles(colloidal) significantly impacted to decrease the sludge filterability by obstructing the water flow. Meyer et al. (2018) reported particle size distribution in bio (secondary) and primary sludge (figure 2.7)**.** Large fraction of biological sludge (secondary sludge) is within the colloidal particle size range. Therefore, bio sludge has lower dewaterability compared to primary sludge. Colloidal particles have more surface area. It has a lower probability to overdose the flocculent and required a higher flocculent dosage to obtain better dewaterability (Merlo et al., 2007).

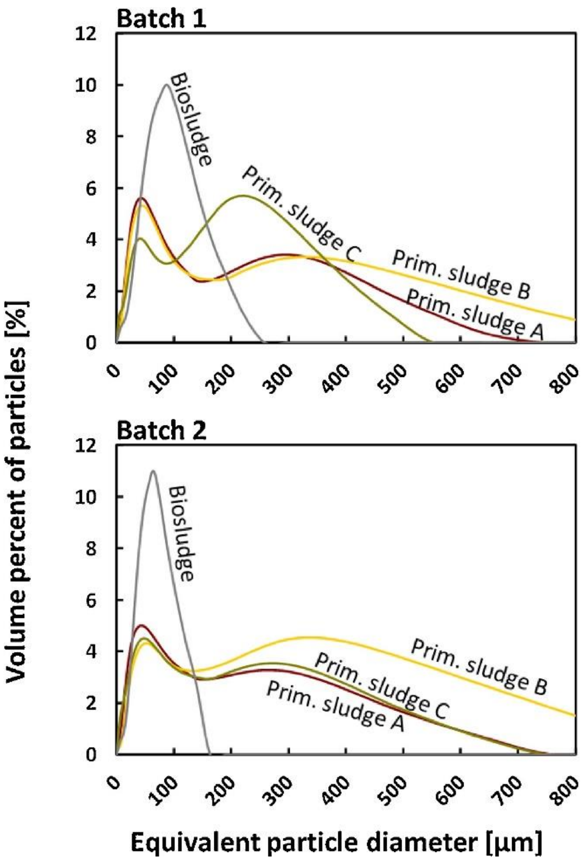


Figure 2.7 *Particle size distribution in primary and bio sludge (Meyer et al., 2018)*

2.6.2 pH

Effects of pH depends on the type of flocculation treatment method. Direct flocculation and coagulation-flocculation are two methods of wastewater treatment. Conventional coagulation-flocculation method has been applied for treating organic or inorganic base wastewater. Such an application is required for pH adjustment in order to obtain complex precipitants. In other hand, direct flocculation with polymeric flocculants has been used for treating organic wastewater(Lee et al., 2014). It has several advantages compared to the coagulation-flocculation method. Polymeric flocculants do not require pH adjustment or addition of coagulant and it produce less sludge volume (Ebeling et al., 2005). Sarika, Kalogerakis and Mantzavinos, (2005) reported direct flocculation of olive mill effluents which can be operated at natural pH(5.4-6.7). They also found that the coagulants such as lime and ferric chloride were extremely pH sensitive and lime coagulation altered the pH of resulting liquid. Effectiveness of direct flocculation can be depended on feed flow composition and characteristics of wastewater such as temperature, pH, ,and hardness (Ebeling et al., 2005).

Another literature stated, polymeric bio-flocculent and iron nanoparticles (FENP) have been used for treating coal mine wastewater. Both flocculants had flocculation activity more than

70% for all pH ranges. Nevertheless, FENP was the most effective flocculate in strong alkaline solution (pH 11) due to the change in surface characteristics or charge of colloidal particles in suspension. Bio-flocculent experienced poor performance in acidic conditions due to the protein denaturation in the bio-flocculent.(Dlamini et al., 2020)

Sabah and Erkan, (2006) showed pH variation effected on flocculation of coal waste slurry. Figure 2.8 shows pH effects on settling rate of flocs and turbidity of suspension after adding anionic flocculants. The coal waste slurry contained Mg^{2+} and Ca^{2+} ions which were acting like natural coagulants. The pH of slurry influenced the activity of such coagulants. Mg^{2+} ions were more active between pH 8-9 while Ca^{2+} ions were more active between pH 10-11. Therefore, pH of feed slurry impacted the activity and stability of those coagulants.

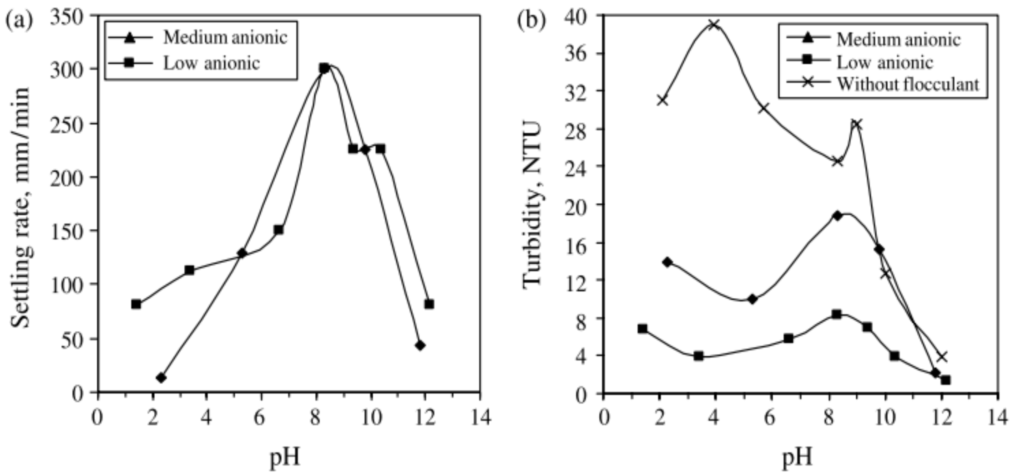


Figure 2.8 *Effect of suspension pH on (a) settling rate and (b) turbidity (Sabah and Erkan, 2006)*

2.6.3 Stirring Rates

Stirring rate is an important parameter in flocculation. According to the stirring rates, flocculation step can be divided into 2 stages, which are mixing and reaction stages. Mixing stage has higher stirring rate compared to the reaction stage. Higher stirring rate provides more collision between SS and flocculent. In a reaction stage, slower stirring rate generates proper turbulence to enhance flocculation. A recent literature reported, turbidity of wastewater could be reduced by 90.96% when stirring rate was 250 rpm for mixing stage and 100 rpm for reaction stage(Zhang, 2017) .

Wang et al., (2020) investigated effects of PAM (Polyacrylamide) on quarts flocculation under different stirring rates.(200, 300, 400, 500 and 600 rpm). Stirring rate influenced the floc formation but also has an influence on breakage of flocs. Higher stirring rate generated higher shear force caused to floc breakage.

2.6.4 Temperature

Temperature of inflow is changed annually due to the climate of the seasons. It impacted the thickening velocity and flocculation. Zhang (2017) conducted experiments with oily wastewater to investigate the effects of temperature on flocculation. They found, when temperature was greater than 45℃, turbidity of the wastewater increased. Because higher kinetic energy at high temperature caused to reduce size of the flocs. However, at low temperature (15℃) had lowest turbidity, which indicated particles had proper kinetic energy and more time for flocculation.

2.6.5 Flocculant Dosage

Higher or lower flocculant dosage causes poor performance in thickening process. At low flocculant dosage, floc size is expected to be small due to insufficient amount of polymer adsorption on to the particles. (Ciftci and Isık, 2017)

The floc size can be increased by increasing dosage of flocculant up to the optimum dosage. Enlarged flocs have higher sludge thickening velocities and settling rates. However, after optimum flocculant dosage, settling rate is almost constant. Over dosage of flocculant makes electrostatic repulsion between flocs and no active sites left on particles for excess flocculant to bind (Kumar et al., 2016). As a result, fewer bonds are formed between flocs, which are leading to form less compact flocs.

Irregular shapes of sludge flocs have been explained by fractal geometry concepts. Two, three, and boundary fractal dimensions of the flocs have been developed by geometry concepts which are represented by D_2, D_3 and, D_B notations respectively. A high D_2, and D_3 value indicates strongly compact sludge floc while a high D_B value indicates a high porous floc structure. (Y. Zhang et al., 2015)

Zhang et al., (2015) studied D_2 and D_3 of the sludge flocs which were produced with different flocculent dosage. According to the figure 2.9b**,** a maximum value of D_2 (1.47) and D_3 (2.21) was reached at 1 ppm flocculent dose. Also, 1 ppm flocculent dose had a better thickening performance according to the figure 2.9a. Hence, strongly compact sludge which was represented by maximum D_2 and D_3 had better thickening performance.

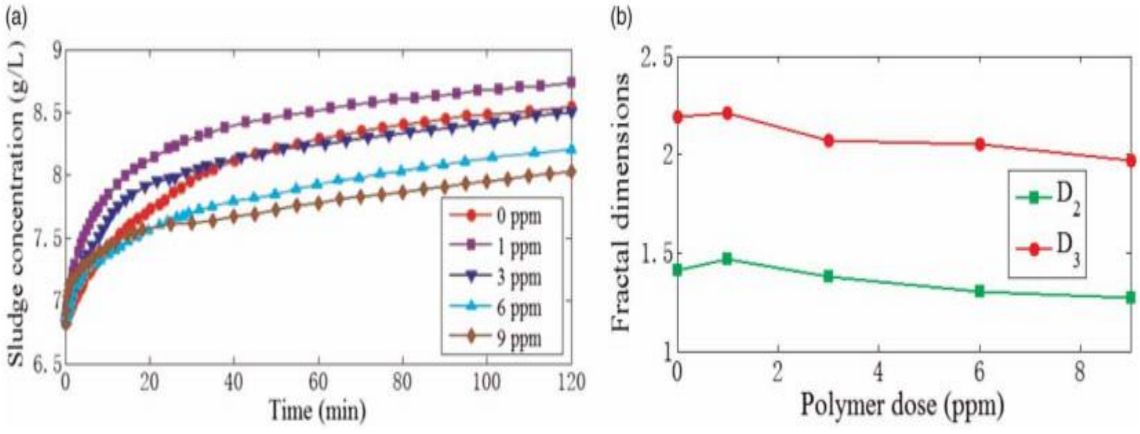


Figure 2.9 *Effect of flocculent dosage on (a) sludge concentration and (b) fractal dimensions(Y. K. Zhang et al., 2015)*

When thickening process is operated under filtration mechanism, specific resistance to filtration (SRF) test can be conducted to find optimum dosage of flocculent. Lowest SRF value of a particular system is relevant to the optimum flocculant dosage (Arhan et al., 1996).

2.7 Overview of SNJ WWTP

The SNJ WWTP receives primarily domestic discharge and surface water from Randaberg, Stavanger, Sandnes, Sola and Gjesdal municipalities. The SNJ WWTP has been in operation since 1992 to 2017 with 240,000 population equivalents (PE). Since 2017, plant has been redesigned with mechanical-biological treatment technologies in order to meet population growth and new treatment requirements. At present the plant has a capacity to treat 400 000 PE BOD load and have an average hydraulic load of 100 000 m^3 d^{-1} (Egeland, 2018). The main sewer system is 35 km long and consists of tunnels, pipe lines (gravity flow and pump line). The main tunnel has 77 000 m^3 volume and act as an equalization reservoir during rainfall periods.

The plant is located at Mekjarvik in Randaberg municipality and wastewater treatment facilities of it are located in a hill (rock) while the sludge treatment facilities such as bio gas plant and fertilizer plant, and administration building are located outside the rock. Treated wastewater is transported by 4 km long outlet tunnel to Håsteinfjorden with 1.2 km from shore line (Razafimanantsoa, 2010).

Figure 2.10 shows process flow diagram of SNJ WWTP. Four pumps with a capacity 1000 L s^{-1} each are used to pump raw wastewater from sewer system to the treatment plant.

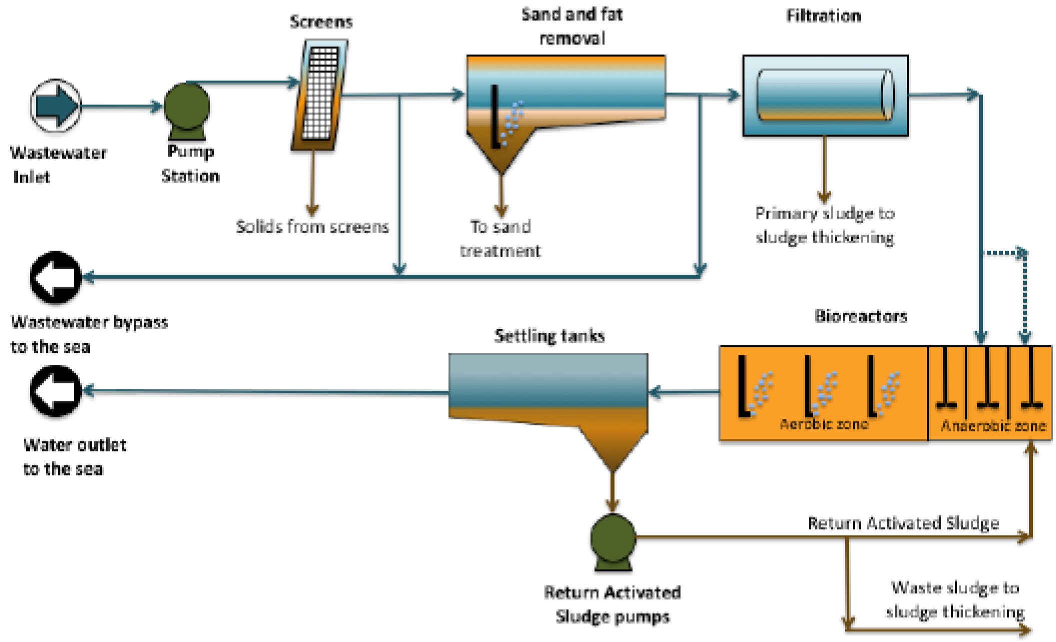


Figure 2.10 *Process flow diagram of SNJ WWTP* (*Egeland, 2018*)

The first step of treatment process is to remove coarse materials from raw wstewater. For that, rotary bar screens (Escamax 6mm) are used to remove paper, plastic, cloths, rags etc. The separated solids from screen are transported to incineration. The raw wastewater without coarse materials flows to the sand and fat removal chamber. Settled sand is removed from the bottom and washed before it is deposited while fat is removed from the top of the chamber and transported to the sludge treatment process. Effluent of sand and fat removal chamber goes to the filtration plant which contains 20 Hydrotech drum filters with 100 µm pore size, designed for 50% of TSS removal.

Hydrotech rotary drum filters used by SNJ WWTP are presented in figure 2.11. Several factors are considered before selecting drum filters. Which are; (1) footprint of method (2) potential for bio gas production (3) energy requirement for operation. SNJ treatment plant is built inside a rock. Hence area availability is a limiting factor for SNJ WWTP. Rotary drum filters utilize lower footprint compares to the sedimentation tanks. On other hand, sludge generated through primary sedimentation has a lower energy potential compared to the microscreen methods. Pauslsrud et al. (2013) reported biomethane potential of sludge generated by sedimentation is reduced due to the hydrolysis during storage. But filtered sludge is fresh and contains high amount of volatile suspended solids increasing the energy generation. Also, rotary drum filters have lower maintenance cost due to few moving parts. Although energy requirement of drum filter depends on backwashing frequency (Xiao et al., 2019). However, there is no equalization tank prior to the drum filters and it has lower buffer capacity against fluctuation in loading.

Dynamic with influent loading is directly affecting the sludge volume and composition. Therefore, strict process control system is required for filter plant. Section 2.6 explains current process control system and variation within sludge volume and sludge composition.

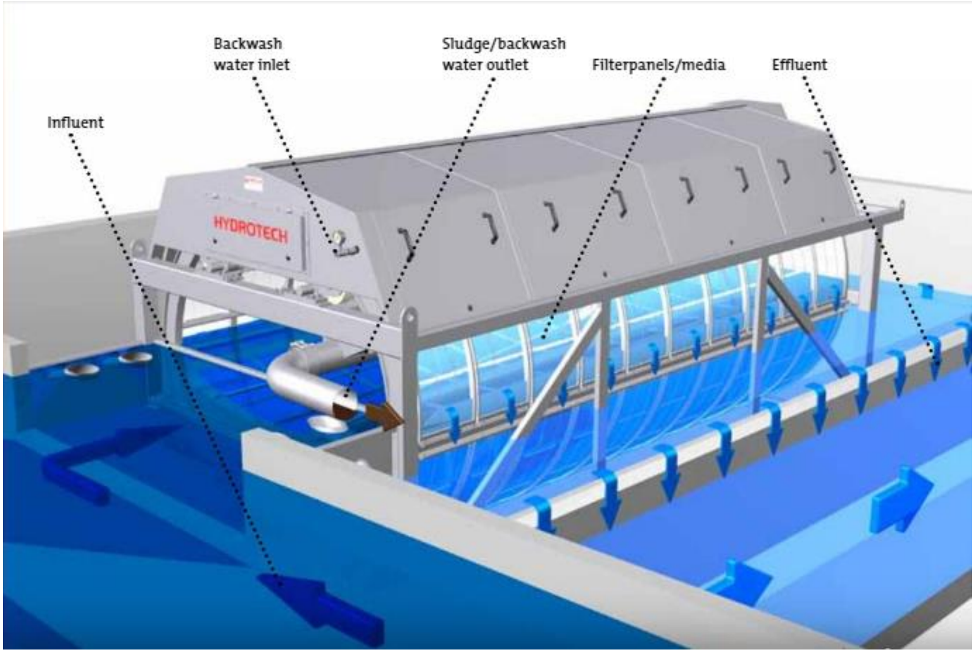


Figure 2.11 *Schematic diagram of Hydrotech rotary drum filter(Eden, 2011)*

The primary sludge is removed from the filter drum with flushing water and is pumped to the sludge thickening process. The outlet stream of filter plant flows to the biological treatment process which consists of anaerobic and aerobic zones for phosphorus and COD removal followed by gravity sedimentation tank. Treated water is thereafter discharged to the sea, while sedimented solids are sent back to the bio reactors as activated sludge. Waste activated sludge (WAS) also called as secondary sludge is pumped to the bio sludge thickening process. Due to the space limitation in SNJ treatment plant, rotary drum thickeners are used to thicken secondary sludge as well as the primary sludge.

Thickened secondary and primary sludge are collected in a sludge holding tank before it is pumped to the buffer tank of sludge treatment. The sludge treatment consists of anaerobic digestion, followed by sludge dewatering and drying.

2.8 Overview of Primary Sludge Thickening Process

Figure 2.12 illustrates process flow diagram of sludge thickening process in SNJ WWTP. Primary sludge from rotary drum filters flows by gravity to the sludge holding tank 1. From there, sludge is pumped to the primary sludge tank which has approximately 100 m^3 capacity. Bio sludge tank receives secondary sludge produced by the bio reactors. Three rotary drum thickeners (Alfa Laval, G3 Mega) are connected with the sludge tanks. Always two out of three sludge tanks are in thickening operation while other thickener is only used during maintenance of one of the thickeners.

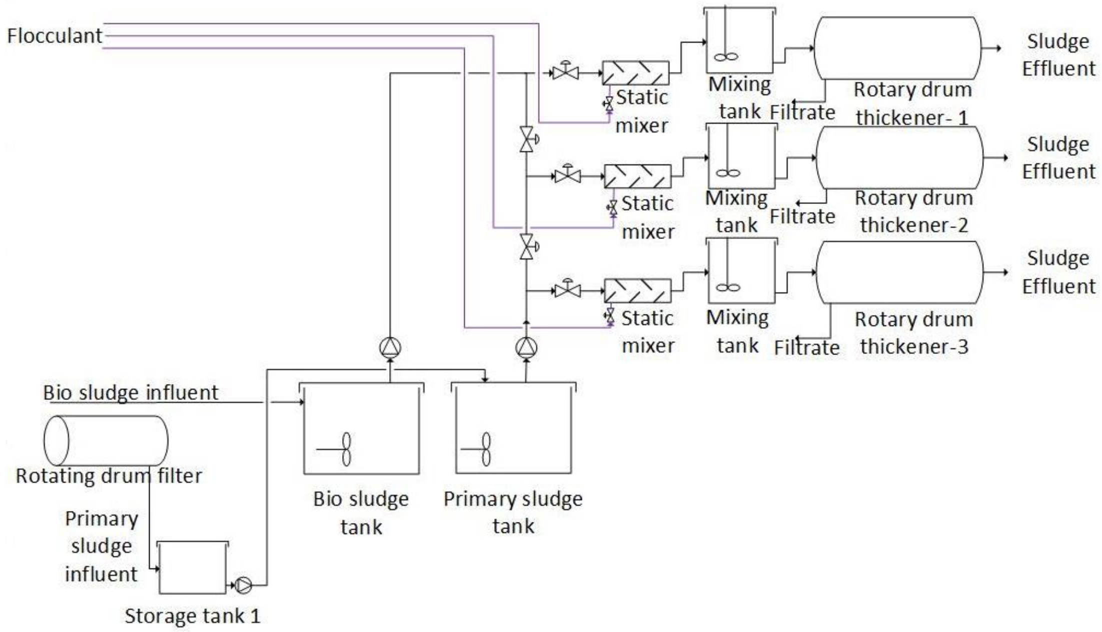


Figure 2.12 *Sludge thickening Process flow diagram of SNJ WWTP*

During this study (1st of January- 31st of March), rotary drum thickeners 1 and 2 were used for thickening secondary and primary sludge respectively. Before entering sludge into the thickener from sludge tank, sludge is mixed with flocculent at the static mixer and moved to the flocculent mixer. Flocculated sludge flows to the perforated rotating drum filter through the inlet pipe. The combination of the rotation and the internal slope (1.5 degree) of the drum, transported sludge to the outlet while dewatering. The liquid level inside the drum filter is retained between baffles due to the integrated scrolls inside the drum (Figure 2.13). During the operation of thickener, process water is sprayed (6.8 m^3h^{-1}) through nozzles in order to clean the drum filter. (Laval, 2011). Thickened primary and secondary sludge are collected to the same sludge holding tank and are pumped to the buffer tank (500 m^3) of digester. Filtrate from thickener is recycled back to the influent of rotary drum filters.

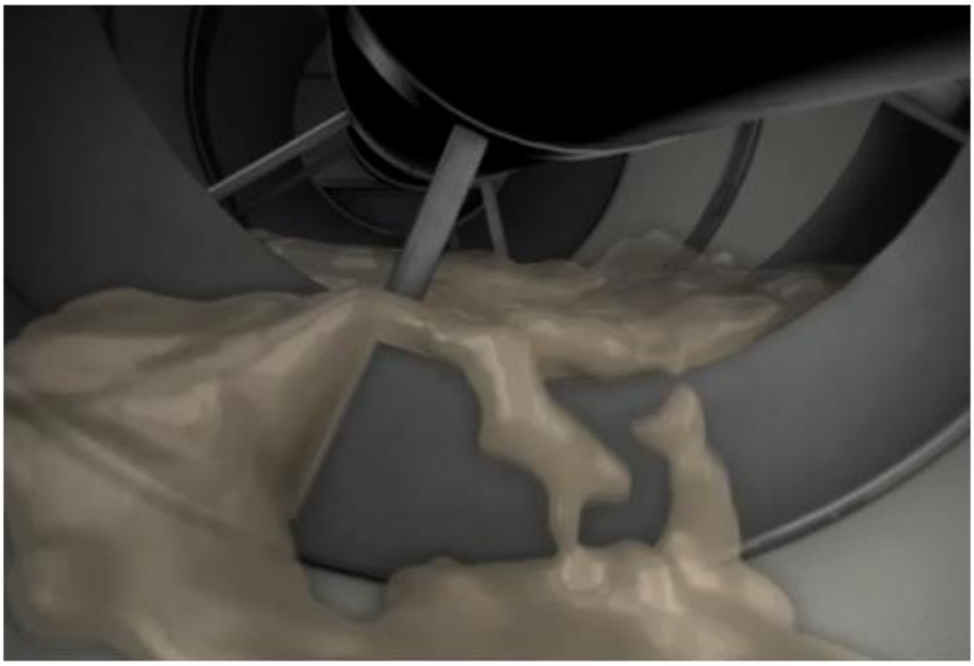


Figure 2.13 *Schematic diagram inside the Alfa Laval rotary drum thickener (Laval, 2020)*

2.9 Mass Balance for Thickening Process at SNJ WWTP

Mass concept helped to understand mass in each stream of the process at a given time. Mass balance concept is developed on the principle that mass neither creates nor destroyed, but can change form. Equation 2.1 was used as the basis to developed mass balance equation for thickening process.

Accumulation = Inflow − Outflow ± Generation ---------- (Equation 2.1)

Thickening process is a separation process. Hence, generation can be equal to zero. Figure 2.14 shows each stream flowrate(Q) and mass (TS) of rotary drum thickener. Equation 2.2 was developed for thickening process at SNJ WWTP by assuming no accumulation inside the drum thickener and zero solid concentration in the backwashing stream. Equation 2.2 can be rearranged to determine flowrate of the filtrate of thickener.

Outflow mass= Inflow mass

$$TS_e\% \times Q_e + TS_r\% \times Q_r = TS_i\% \times Q_i \,;$$

Outlet flowrates= inlet flowrate

$$Q_e + Q_r = Q_i + Q_b \,;$$

$$TS_e\% = \frac{Q_i TS_i\% - Q_r TS_r\%}{Q_i - (Q_r - Q_b)} \text{ ---------(Equation 2.2)}$$

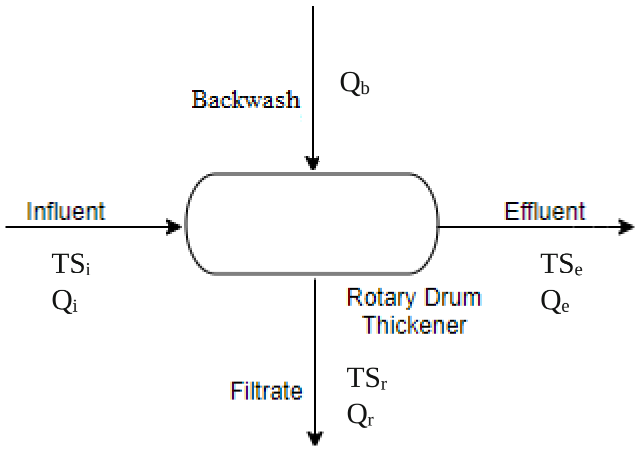


Figure 2.14 *Notations of mass and flowrate of each stream in rotary drum thickener*

2.10 Process Controlling Loop of Rotary Drum Filter at SNJ WWTP

Current process control system of rotary drum filter was initiated on July 2018. All drum filters are available at all time. Backwashing frequency is changed in order to retain level of the inlet channel at 2.75 meters and backwashing time period is fixed at 30 seconds. All filters are grouped into five groups and are backwashed each group sequentially with hot water. Table 2.3 describes pause period between two backwash cycles when inlet flow level at high and low. Overall, at higher level has higher backwash frequency compared to the lower level of inlet.

Table 2.3 *Pause period of backwashing mechanism at inlet high and low level*

Inlet Level (m)	**Pause Period Between Two Backwashing Circles (s)**
<2.75	up to 60
>2.75	7-8

Due to this controlling method, sludge produced in the filters varies in volume and solid concentration with influent flowrate and are shown in figure 2.15 and figure 2.16 respectively.

According to the figure 2.15, Sludge volume is increased when influent flowrate to the filter increase. During rainfall periods, higher influent load is received to the drum filters. Due to that, backwash frequency is increased to keep the set point of influent level and produced more sludge volume for thickening operation.

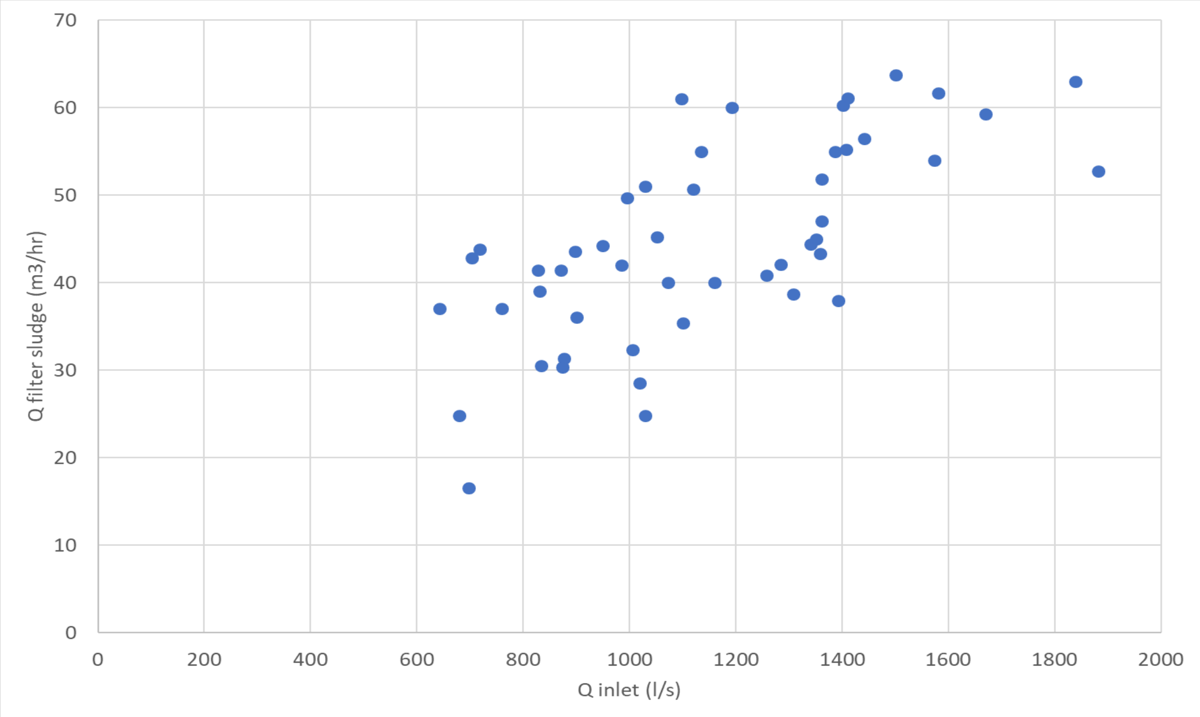


Figure 2.15 *Sludge volume variation with influent flow to the rotary drum filter at SNJ WWTP(Ydstebø and Egeland, 2019b)*

However the higher backwash freaquency resulted in producing dilute primary sludge. That is explained in figure 2.16. As well as during such periods, wastewater contains lower amount of suspended solids compared to the dry weather periods and lower filtration time caused to further reduce solids concentration in primary sludge. However, at lower influent flowrates, it caused to increase filtration time period and lower backwash frequency. Therefore, at low level it has higher solid concentration and lower sludge volume in primary sludge compared to the high level of influent. Overall, higher sludge volume has lower solids concentration and lower sludge volume has higher solids concentration. Therefore, sludge loading to the thickener is more or less the same (10 tonns TS d^{-1}). Current controlling methods removed suspended solids more than 50%. Sludge thickening facility should be able to handle this sludge composition and volume variation. For that, larger sludge holding tank or tight process control system for thickener is necessary. Designed primary sludge holding tank is not large enough to handle this variation and designing a larger sludge holding tank is not possible due to area limitation in the SNJ WWTP. Therefore, strict process controlling system is mandatory for primary sludge thickener in order to handle sludge volume and composition variation.

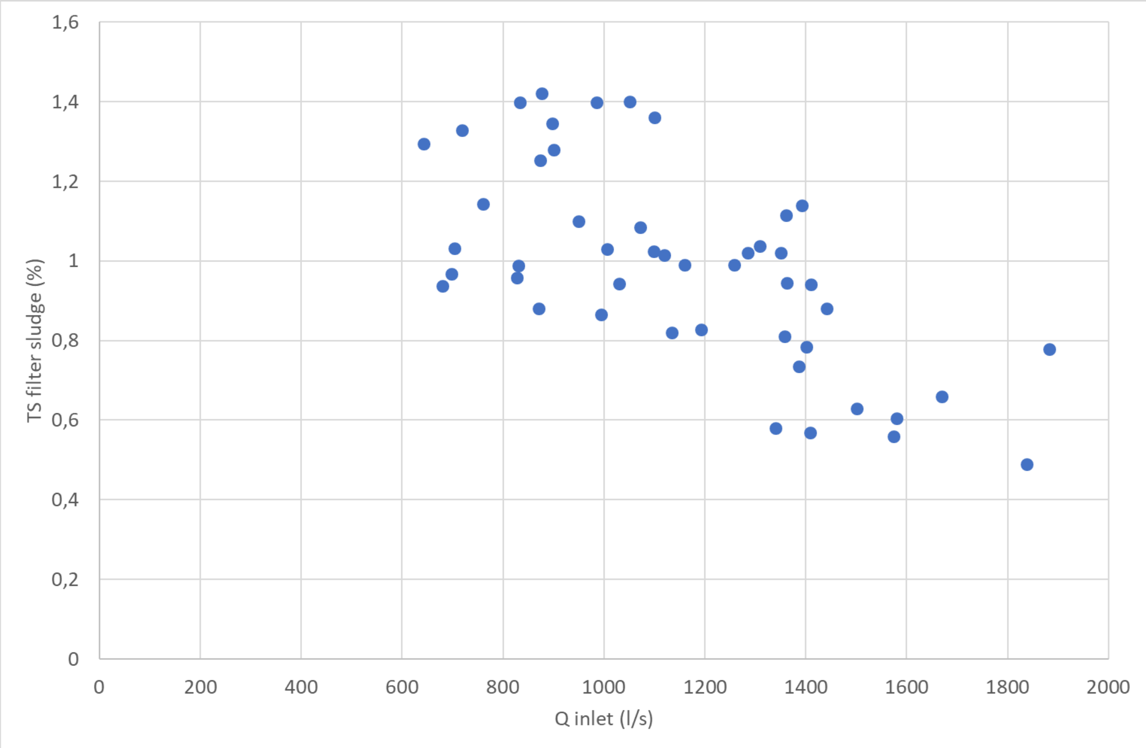


Figure 2.16 *TS % in primary sludge with respect to the influent flowrate of rotary drum filter at SNJ WWTP (Ydstebø and Egeland, 2019b)*

2.11 Process Controlling Loop of Rotary Drum Thickener at SNJ WWTP

The objective of sludge thickening process is to obtain constant 5% TS in thickened sludge before pumping it to the buffer tank of anaerobic digester. The sludge produced in the filter plant is around 1 % TS and TS of thickened sludge is determined by many factors, and poor process control caused to change solids concentration dramatically in thickenrf sludge. The operational consequences are significant in both lower or higher TS than the 5%. Too low TS produces high volume of diluted sludge. That results in reduceing the SRT of the digester and lowerng biogas production. If the TS is too high the sludge can not be pumped from sludge holding tank to the buffer tank. Currently, such sludge is diluted with water in order to be able to pump it. Diluting concentrated sludge is an extra process step due to poor process control. Overall, poor process control of thickener impacted the downstream processes economically and operationally. There are 3 process control systems that has been implemented to the rotary drum thickener in order to get 5% TS from thickened sludge. All these control methods are used different control variables to manipulate floccuelnt dosage.Three methods are;

1. Influent flow proportional floccuelnt dosage
2. Influent mass proportional floccuelnt dosage
3. Rotary drum load proportional floccuelnt dosage

2.11.1 Influent Flow Proportional Flocculent Dosage

Figure 2.17 shows solids concentration and flowrate of influent to the thickener between 2017-2019. Influent flowrate to the thickener was almost constant at 50 $m^3 h^{-1}$ between 2017 to July 2018. However after July 2018, current controlling method of the drum filters was installed and that resulted in produceing inconsistent primary sludge volume. Therefore, influent flowrate of the thickener was varied between 40 $m^3 h^{-1}$ - 90 $m^3 h^{-1}$.

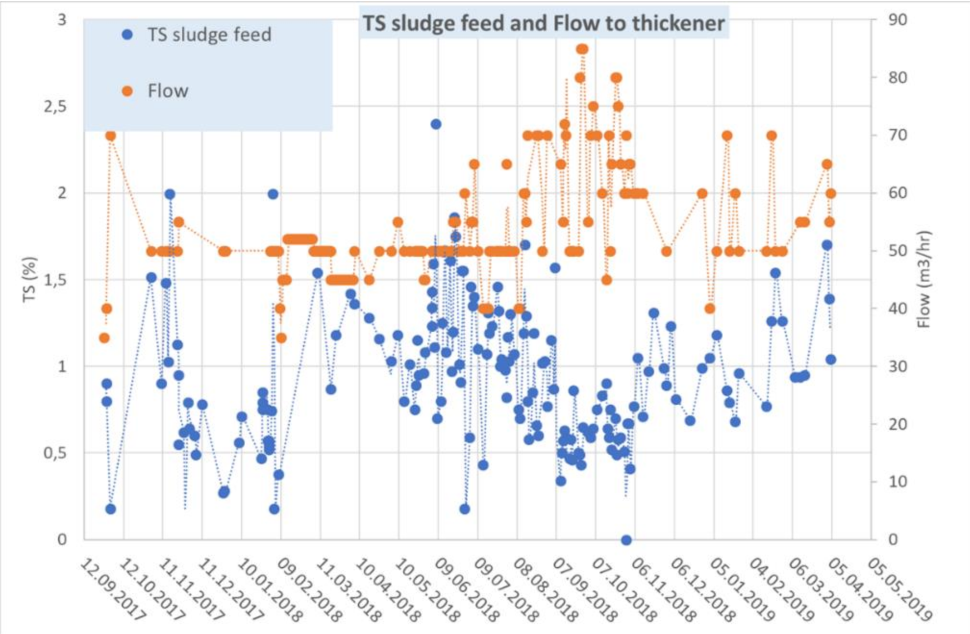


Figure 2.17 *TS and flowrate of primary sludge influent to the thickener at SNJ WWTP(Ydstebø and Egeland, 2019a)*

Flow proportional control method of drum thickener was a feedforward method and was operated during 2017-2018. Figure 2.18 shows TS of thickened sludge when flocculent dosage (g flocculent/ m^3 influent) is constant at 7.68. Average TS was around 5% but TS deviated between 0.5% to 14%. Flow proportional control method was not within acceptable range of deviation for TS in thickened sludge (5% ±1). This was because sludge composition was changed even though flowrate was constant. This method suggests solid concentration is a crucial parameter for sludge thickening process.

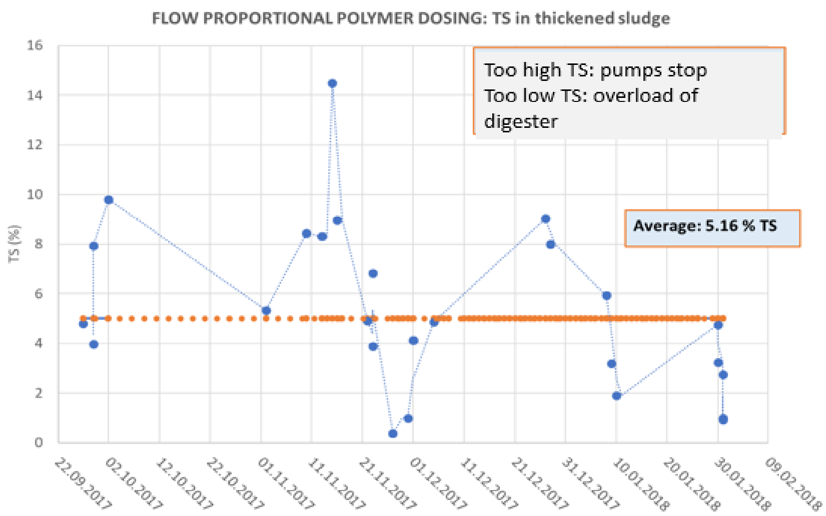


Figure 2.18 *Effluent TS variation by flow proportional flocculent dosing controlling method from 2017-2018*(*Ydstebø and Egeland, 2019a*)

2.11.2 Influent Mass Proportional Flocculent Dosage

Mass proportional control method was also a feedforward control method, where influent solids load was measured to control the flocculent flowrate. Theoretically, optimum flocculent dosage is constant for specific solids load. Figure 2.19 illustrates TS of thicken sludge with respect to the flocculent dosage (g flocculent/kg TS) over 2017-2019. It was not possible to obtain 5% TS of thickened sludge by one fixed flocculent dosage even for constant flowrate to the thickener. A variable influent flowrate has been used since 2018. It caused to change HRT of thickening and furthermore complicated to control the thickening process. However, higher flocculent dosages caused to the high TS in thickened solids. Therefore, flocculent dosage plays a vital role for thickening process. During 2018, online, TS% measuring instrument was installed to the influent of the primary sludge thickener.

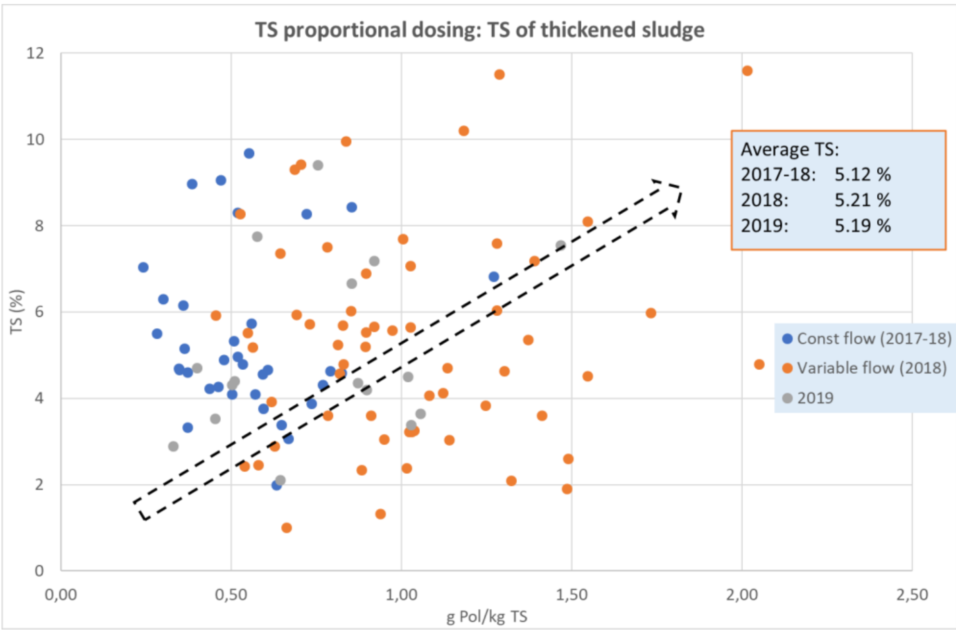


Figure 2.19 *Effect of flocculent dose to the effluent TS between 2017-2019*(*Ydstebø and Egeland, 2019a*)

2.11.3 Rotary Drum Load Proportional Flocculent dosage

Currently, this method is used to control primary sludge thickener and considered as feed backward control method. Amperes on the drum thickener are used to manipulate flocculent dosage to the influent sludge load. Influent flowrate is set manually. Ampere values explain sludge load inside the drum thickener. At low amperes (< 0.90) drum thickener will have a low load and thickened sludge will be diluted. At high amperes (> 1.0) drum thickener will have high load and sludge will be concentrated. Ampere set point of particular sludge has to be selected by the operator through visual inspection of thickened sludge or pumping flowrate of thickened sludge to the buffer tank. If the actual ampere is lower than the set point, then system will increase flocculent flowrate until desired ampere is achieved. Vice versa for higher actual ampere than set point.

The flocculent dosage is also regulated by the flow on the pumps which pump thickened sludge to the buffer tank. A minimum and a maximum flowrate is set in order to control ampere set point. If the flow becomes higher than the maximum flow, the set point for amperes is automatically reduced to give less concentrated sludge until the desired pressure is reached.

If the flow is lower than the minimum pressure, the set point for amperes is automatically increased to give a more concentrated sludge until the desired pressure is reached. Figure 2.20 illustrates TS of thickened sludge during 2020 under this feedback control method. Average TS is around 5% and it varied between 10%-2%. This method has lower deviation compared to the feedforward control methods but it is not within the acceptable TS range. This control method is not a fully automated control method. Therefore, it required more attention to the thickening process.

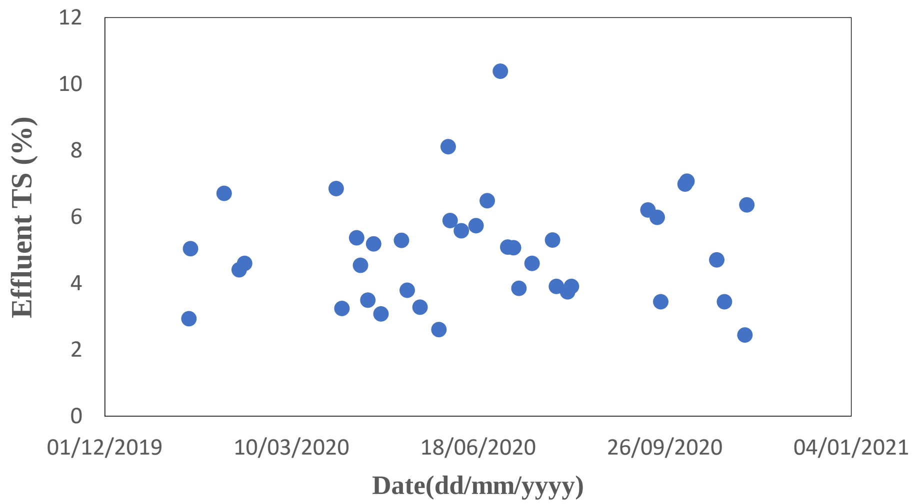


Figure 2.20 *Effect on effluent TS under thickener drum load proportional controlling method during 2020* (*Ydstebø and Egeland, 2019a*)

2.12 Research Gap

Among the WWTPs in European Union (EU), SNJ WWTP is the largest plant using RDTs as primary treatment method and RDTs are relatively new primary treatment methods. Therefore, there is lack of literature papers about characteristics of primary sludge generated by rotary drum filters and thickening of such sludge. As well as, effect of mixed sludge (secondary and primary sludge) at SNJ WWTP on dewaterability is an interesting research area to conduct. Combination of RDFs and RDTs is an uncommon treatment method in WWTPs. As a result, very lower number of research has been conducted with rotary drum thickener and neither of that research described effect of operational parameters of rotary drum thickener to the thickening process.

Effluent of primary sludge thickener varied beyond the acceptable range of TS% of 5±1% under current controlling method. Therefore, new controlling method is essential to overcome consequences in downstream process for effluent solid concentrations beyond expected limit. According to the author's knowledge, research papers have not been published regarding development of process controlling loop for rotary drum thickener.

2.13 Objectives

The objectives of this master's thesis are developed through research gap of the primary sludge thickening process at SNJ WWTP. The main objective of this study is to develop controlling loop for primary sludge thickening process to obtain expected effluent solid concentration (5±1% TS). The other objectives are;

1. Characterizing primary sludge and evaluating effect of them on dewaterability of flocculated primary sludge through laboratory scale experiments.
2. Analyzing the effect of different mixed sludge ratios on dewaterability and investigating whether it is possible to obtain consistent dewaterability by constant flocculent dosage for mixed sludge through laboratory scale experiments.
3. Investigating the effect of operation parameters of rotary drum thickener such as rotational speed, backwash mechanism, flocculent dosage on effluent TS% and filtrate turbidity.
4. Evaluating possible feedback and feedforward parameters of thickening process and development of most reliable and economically viable controlling loop for primary sludge thickening process.

3. Materials and Methods

Laboratory scale and full-scale experiments have been conducted to investigate the effect of operational parameters of primary sludge thickening process in SNJ WWTP. Jar tester was used for laboratory scale testing and rotary drum thickener was used for full scale experiments. This chapter also includes analytical methods used in this study. All laboratory works were conducted at the SNJ process laboratory.

3.1 Laboratory Scale Experimental Procedure for Primary Sludge

One of the main objectives of this study is to find out optimum flocculent dosage for primary sludge. Primary sludge influent samples were collected at the sampling point 1 as indicated in figure 3.1. Flocculation tests were conducted for the collected samples on 8 different days and optimum flocculent dosage was determined by time to filter and filtrate turbidity tests.

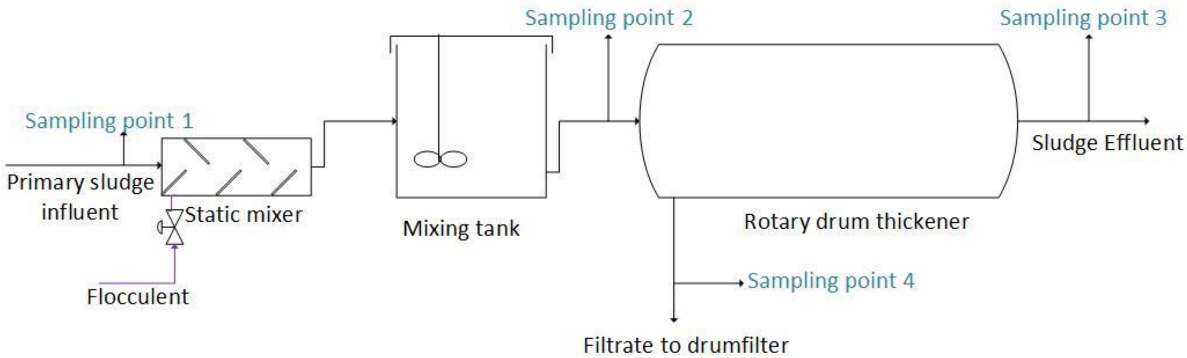


Figure 3.1 *sampling points of primary sludge thickening process at SNJ WWTP*

3.1.1 Flocculation Test (Jar Test)

Wastewater characteristics such as pH, alkalinity, conductivity, TS, TSS, and turbidity of supernatant were measured for collected sludge samples. 200 ml of homogenous sludge samples were added to the 6 beakers (500 mL) and were placed in a jar tester (VELP FC6S). Different volumes of 0.09% (w/w) flocculant (CC FLOC D 6144K) were added to each beaker using a pipette (Thermo Fisher Scientific) in 1-9 mL range. The mixing speed was set at 30 rpm for 10 minutes. After flocculation, the mixing was turned off and time to filter and filtrate turbidity tests were conducted.

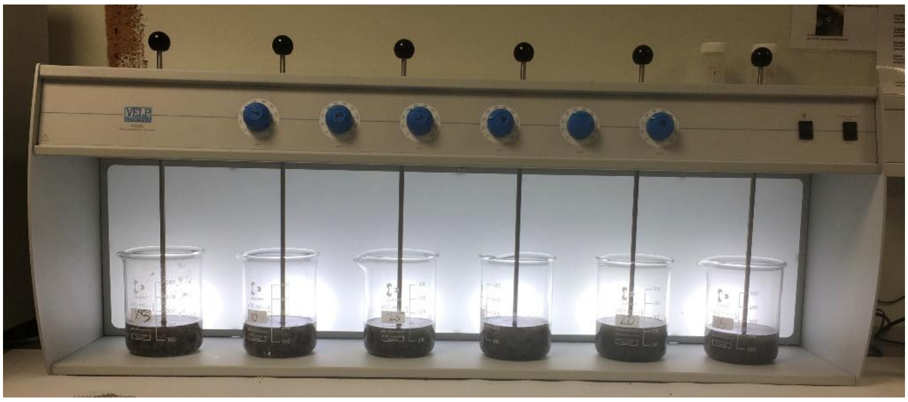


Figure 3.2 *Jar tester with primary sludge samples for flocculation test*

3.1.2 Time-to-Filter Test

Dewaterability of flocculated primary sludge was determined through time to filter test. Figure 3.3 shows experimental setup used to determine Time to filter test (TTF). A filter paper (Whatman No. 1) of diameter 90 mm and pore size 11 μm was placed in a funnel and sealed by prewetting with a small volume of distilled water while vacuum was turned on. TTF was carried out for each sample after flocculation test according to the SM 2710H standard method (Eaton et al., 2005). The flocculent dosage range was determined as the dosage which resulted in a time to filter value below 40 seconds.

Figure 3.3 *Time to filter experimental setup*

3.1.3 Filtrate Turbidity Test

In full scale process at SNJ WWTP, flocculated sludge was thickened through a perforated drum filter. Hence, quality of filtrate after flocculation was determined at laboratory scale by "filtrate turbidity test". Flocculation tests were repeated with similar flocculent dosages used for time to filter tests. After flocculation, filtration was performed using a stainless-steel sieve (VWR) with nominal mesh size 1 mm. The turbidity of the filtrate was measured using a turbidity meter (HACH 2100N).

3.2 Laboratory Scale Experimental Procedure for Mixed Sludge

This study was conducted to investigate effect of mixed sludge (secondary and primary sludge) to the flocculation. Secondary sludge and primary sludge samples were collected from the influent of respective thickeners. Procedures described in flocculation test (section 3.1.1) and TTF test (section 3.1.2) were used to determine optimum flocculant dosage for primary and bio sludge. Optimum flocculant dosage for primary sludge was determined, when time to filtration reached to the 25±5 seconds. For bio sludge, it was 50±5 seconds.

200 mL of homogenous mixed sludge samples were prepared according to the table 3.1 and was added to the 5 beakers (500 mL). Thickening process at SNJ WWTP received a lower flowrate of secondary sludge (around 25 m^3 h^{-1}) compared to the primary sludge (around 65 m^3 h^{-1}). For that reason, 5 different mixed sludge ratios were selected with lower or equal secondary sludge volume compared to the primary sludge.

Flocculation test (section 3.1.1) and TTF test (section 3.1.2) were conducted for mixed sludge. The flocculant dosage added for mixed sludge was sum of the dosages resulted by optimum flocculant dosage for primary sludge and optimum dosage for bio sludge taken in the ratio similar to mixed sludge. The calculation of flocculent dosage of mixed sludge was included in Appendix 3.2. This study had been conducted for sludge samples taken on 3 different days.

Table 3.1 *Primary and secondary sludge volumes in mixed sludge samples*

Secondary Sludge (mL)	Primary Sludge (mL)	Secondary: Primary Sludge Ratio
20	180	1:9
40	160	1:4
60	140	3:7
80	120	2:3
100	100	1:1

3.3 Full Scale Experiments with Rotating Drum Thickener

Full scale experiments have been conducted to investigate effect of operational parameters (flocculant dosage, flocculator mixing speed, rotational speed of drum filter, and backwash time period of drum filter) to the primary sludge thickening process at SNJ WWTP. Primary sludge samples were collected before and after completing full scale experiments which were used to determine sludge characteristics such as TS, TSS, conductivity and turbidity.

3.3.1 Flocculant Dosage

This study was conducted by varying 0.09% (w/w) flocculent dosage (CC FLOC D 6144K) at specific influent flowrate to the drum thickener. 3 different influent flowrates ($50m^3h^{-1}$, $65m^3h^{-1}$, $71\ m^3h^{-1}$) were maintained during the experiment. Other controlling parameters were fixed according to the table 3.2. Flocculant dosage was changed and waited 10 minutes before taking samples. Samples were collected as grab samples from flocculent mixer (S.P 2), sludge effluent (S.P 2) and filtrate (S.P 3) of the thickener. Similar procedures were conducted for different flocculent dosage levels and samples were collected at each level. TTF was measured for samples collected from flocculent mixer. Effluent sludge samples were used to measure TS percentage and turbidity of filtrate measured using a turbidity meter (HACH 2100N). This study has been conducted for 5 different days under 50 and 65 $m^3\ h^{-1}$ and 3 different days under 71 $m^3\ h^{-1}$.

Table 3.2 *Rotary drum thickener fixed controlling parameters*

Flowrate ($m^3\ h^{-1}$)	**Flocculator Mixer Speed (rpm)**	**Rotational Speed of Drum Filter (rpm)**	**Backwash Mechanism; Backwash (s) /Pause (s)**
50/65/71	50	4.8	20/10

3.3.2 Flocculator Mixer

This experiment was conducted to investigate the effect of flocculator mixing speed to the flocculation. Influent flow rate was fixed at 65 $m^3\ h^{-1}$ and flocculent dosage was fixed at a consistent rate. Flocculent mixer was turned on and waited 5 minutes to stabilize the flocculation process. After 5 minutes, sample was collected from effluent of the flocculator mixer. Mixer was turned off and sample was collected from flocculator after 5 minutes. Similar procedure was used to collect samples for 45 $m^3\ h^{-1}$ and 55 $m^3\ h^{-1}$. When reducing flowrate, flocculent dosage was reduced by same percentage to the flowrate reduction. TTF was measured for each collected sample. This study has been conducted on 3 different days.

3.3.3 Rotational Speed of Drum Filter

Table 3.3 describes all the operational parameters which were fixed during the experiment. Four different rotational speeds of drum filter (1.6, 3.2, 4.8, and 6.4 rpm) were used in this study, to determine the effect of rotational speed to the sludge retention time. Rotating drum thickener was operated minimum 10 minutes at specific rotational speed before collecting samples from sludge effluent and filtrate of the thickener. TS was measured for collected sludge effluent samples and filtrate samples were used to determine turbidity. This study has been conducted for 3 different days.

Table 3.3 *Rotary drum thickener fixed controlling parameters*

Flowrate (m^3 h^{-1})	**Flocculator Mixer Speed (rpm)**	**g Flocculent /kg TSS of Influent**	**Backwash Mechanism; Backwash (s) /Pause (s)**
65	50	1.3±0.1	20/10

3.3.4 Backwash Mechanism of Rotation Drum Thickener

The objective of this study is to understand how long can filter of drum thickener can effectively filtrate without backwashing. Influent flow rate was fixed at 65 $m^3 h^{-1}$ and flocculant dosage was fixed at a constant rate. After completing backwash circle, stopwatch was turned on and samples were collected at different time intervals (1, 4, 7, 9 minutes) from thickener sludge effluent and filtrate. TS was measured for collected sludge effluent samples and filtrate samples were used to determine turbidity.

3.4 Analytical Methods

Grab sample was shaken in order to obtain a homogeneous sample before conducting analytical experiment. The used analytical methods TS, TSS, conductivity, pH, turbidity and alkalinity are described in this chapter.

3.4.1 Total Solids (TS)

TS was measured for samples collected from influent and effluent of the primary thickener. The modified standard method (SM 2540 G) was used to determine total solids. 25-50 mL of sludge sample was added to the aluminum evaporating dish and kept it in a drying oven (Fermaks TS9053) over night at 105 ℃. TS was analyzed in duplicates for each sludge samples in order to minimize error generation due to uneven distribution of solids in sludge samples.

3.4.2 Total Suspended Solids (TSS)

TSS was measured according to the standard method (2540 D) for samples collected from influent to the thickener and filtrate of the thickener. 3-6 mL of influent sample or 50 mL of filtrate sample was filtered through a filter (diameter 47 mm Whatman GF/C) with 1 μm pores and dried at 105 °C in a drying oven (Fermaks TS9053) for 2 hours.

3.4.3 Alkalinity and Volatile Fatty Acid (VFA)

VFA and Alkalinity analysis was determined based on five pH point titration procedure, which was developed by Moosbrugger et al., (1993) **.** Sample was collected from influent of the thickener was used to determine alkalinity and VFA. 100 mL of collected sample was centrifuged and filtered through a filter paper (diameter 47 mm Whatman GF/C). 50 mL of filtered sample was placed on a magnetic stirrer with low rotational speed (< 10 rpm). The initial pH of the sample was recorded and titrated with HCl (0.05 M) to 4 different pH points (6.7 ± 0.1, 5.9 ± 0.1, 5.2 ± 0.1, and 4.3 ± 0.1). Volume of HCl consumed for each pH point was used to analyze alkalinity and VFA through TITRA 5 software. The software calculates alkalinity as mg CaCO3 L^{-1} and the total VFA concentration expressed as mg HAc L^{-1}.

3.4.4 pH and Conductivity

PH and conductivity were measured for samples collected from influent of the thickener.
pH meter (VWR pHenomenal 1100 L) was used to measure pH and portable meter (WTW Multi 3630 IDS) was used to measure conductivity. Table 3.4 describes probe and calibration method of each instrument. 50-100 mL of sample was placed on a magnetic stirrer and immersed into the samples until the value was constant.

Table 3.4 *Probe and calibration method of pH and conductivity meter*

Parameter	Probe	Calibration Method
Ph	VWR pHenomenal LS221 probe	weekly with pH 4, 7 and 10 buffers.
Conductivity	WTW Tetracon 925	Weekly with a standard KCl solution

3.4.5 Turbidity

Turbidity was measured for samples collected from influent and filtrate of the thickener using a turbidity meter (Hack 2100N). 1 L of influent sample was kept in an Imhoff cone for 1 hour of sedimentation. 30 mL of supernatant was added to the sample cell and outside of the cell was wiped using a clean tissue. Filtrate sample was also mixed well and added to the turbidity cell. Sample was mixed to disperse solids and turbidity measured directly from turbidity meter. Standards calibration kit (Hack stablcal 2662105) was used to calibrate turbidity meter weekly.

4. Results and Discussion

Results of laboratory scale experiments and full-scale experiments are presented and discussed in this chapter. At the end, five different controlling loops are developed for primary sludge thickening process in order to obtain expected effluent solid concentration. All the raw data and calculations corresponding to the figures and table in this chapter are presented in the Appendix.

4.1 Laboratory Scale Experiments for Primary and Mixed Sludge

This sub chapter is further divided into four sections: (a) characteristics of primary sludge, (b) time to filter and filtrate turbidity tests, (c) factors affecting flocculation and dewaterability, and (d) flocculation test for mixed sludge.

4.1.1 Characteristics of Primary Sludge

Wastewater characteristics (TS, TSS, Turbidity of supernatant, Conductivity, Alkalinity, Fatty acid and pH) are tabulated in table-4.1 for primary sludge samples collected on 8 different days. Those sludge samples were further investigated through time to filter and turbidity of filtrate tests and presented on section 4.1.2 and 4.2.3. The errors of TS% and TSS were determined using t-distribution analysis with 90% of certainty. All parameters except pH showed considerable variations. pH remained nearly constant around 6.9. The temperature of primary sludge is also kept constant around 5 ℃. The TSS represents the particulate solids in which particle size is greater than 1 µm. The mean value of TSS to TS ratios was calculated to be 0.77±0.04 (Appendix 4.1)**.** Primary sludge produced by rotary drum filter was dominated by particulate fraction (TSS) due to its pore size (100 µm). Primary sludge concentration (TS or TSS) was influenced by weather conditions of the region and backwash mechanism.

Table 4.1 *Characteristics of primary sludge samples obtained on 8 different days*

Day	TS %	TSS ($g\ L^{-1}$)	Turbidity of Supernatant of Influent (NTU)	Conductivity (mS/cm)	Alkalinity (mg $CaCO_3$ L^{-1})	VFA (mg HAc L^{-1})	pH
1	0.92±0.09	6.71±0.54	220	3.72	109.8	16.7	6.8
2	1.07±0.02	7.73±0.57	230	4.48	131.4	16.9	6.9
3	0.62±0.02	4.71±1.02	150	2	75.2	0.1	6.8
4	0.81±0.01	6.06±0.97	250	3.2	125.4	11.9	7
5	1.44±0.14	11.7±0.1	320	2.52	151	23.5	6.9
6	1.34±0.04	10.87±0.50	450	2.96	139.9	31.2	6.8
7	1.39±0.03	11.25±0.81	400	3.12	144.8	27.1	6.8
8	1.02±0.05	8.03±1.37	240	3.67	168.3	17.9	7.1

Several correlations were observed by analyzing characteristics of primary sludge. Figure 4.1a and 4.1b show turbidity of the supernatant with respect to the TS and VFA concentrations of primary sludge respectively. Figure 4.1a shows increasing trend between turbidity of supernatant and TS of primary sludge. Primary sludge contained negligible amount of dissolved solids as most of the dissolved solids moved to the biological treatment plant through rotary drum filters. Therefore, larger fraction of difference between TS and TSS of primary sludge would be colloidal solids. As a result, the fixed ratio between TS/TSS of primary sludge was most likely to increase colloidal solids concentration when TS of primary sludge increased.

Turbidity of supernatant had a better correlation with VFA compared to the TS of primary sludge. VFA concentration increased when influent sludge to the treatment plant hydrolyzed under anaerobic condition of the sewer system (Ødegaard, 1998). Septic sludge (hydrolyzed sludge) received to the treatment plant due to the regional weather condition. During heavy rainfall period, treatment plant received fresh sludge (without hydrolyzed) and more septic sludge on dry weather condition. Septic sludge was produced through hydrolyzation of particle matters. It resulted in increasing the colloidal solids in the influent of the treatment plant. Hence, higher VFA concentration represented higher colloidal solids concentration in the primary sludge. According to the previous studies, the turbidity of supernatant was mainly caused by the colloidal of the non-settleable solids (Tarleton, 2014). Therefore, linear relationship between VFA and turbidity of supernatant was possible to observe.

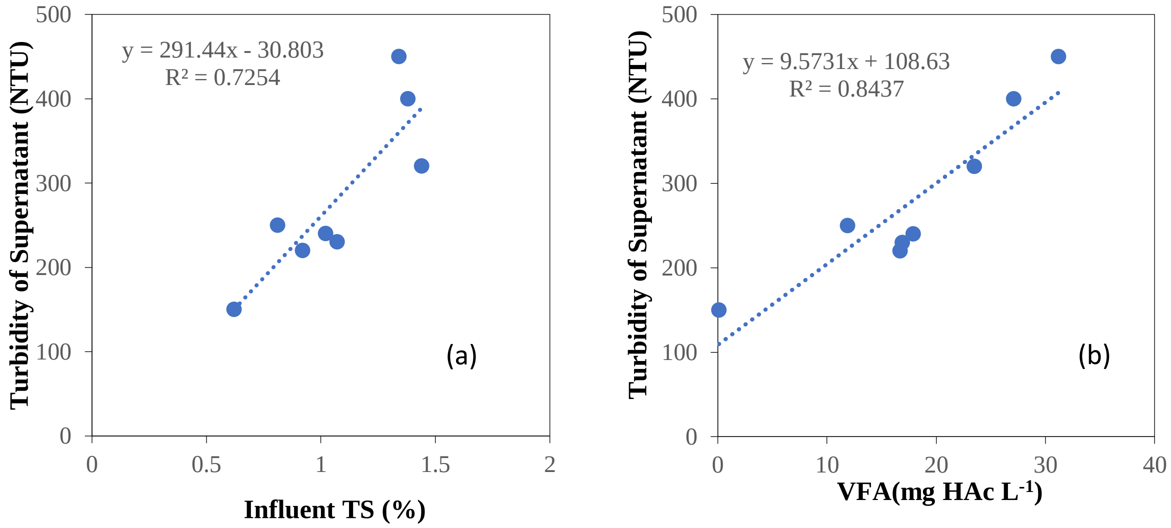


Figure 4.1 *The relationship between turbidity of supernatant with (a) TS and (b) VFA concentration of primary sludge*

Figure 4.2 represents influent VFA concentration and conductivity on 8 different days. Septic sludge produced higher VFA which resulted in increasing the conductivity of the primary sludge. However, according to the figure 4.2, highest conductivity was not reached at highest VFA concentration. Hence, other factors influenced the conductivity of the primary sludge. Egeland (2018) reported Influent of SNJ WWTP was subjected to seawater inflow when the tide level was high. Therefore, sea water concentration in primary sludge was another possible factor to increase conductivity.

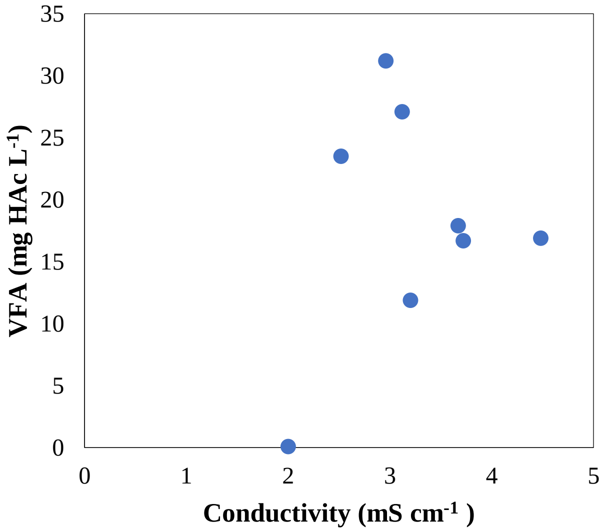


Figure 4.2 *Conductivity vs VFA concentration in primary sludge*

4.1.2 Time to Filter Test for Primary Sludge

This test was conducted to investigate dewaterability of the primary sludge. The time to filter of the primary sludge was measured with respect to the increasing flocculent dosage on 8 different days as shown in figure 4.3. It was expected that the curves in the figures to be coinciding if the sludge characteristics remained unchanged. But non-coincident curves were obtained indicating different time to filter values for the same flocculent dosage (g flocculent/kgTS)

According to the figure 4.3, initially the time to filter value decreased with the increasing flocculent dosage and reached a minimal value because of aggregation of most of the colloidal solids of primary sludge. When further increasing the flocculent dosages, time to filter value increased due to clogging of the filter paper by accumulation of free flocculants, or remained consistent at the minimum value.

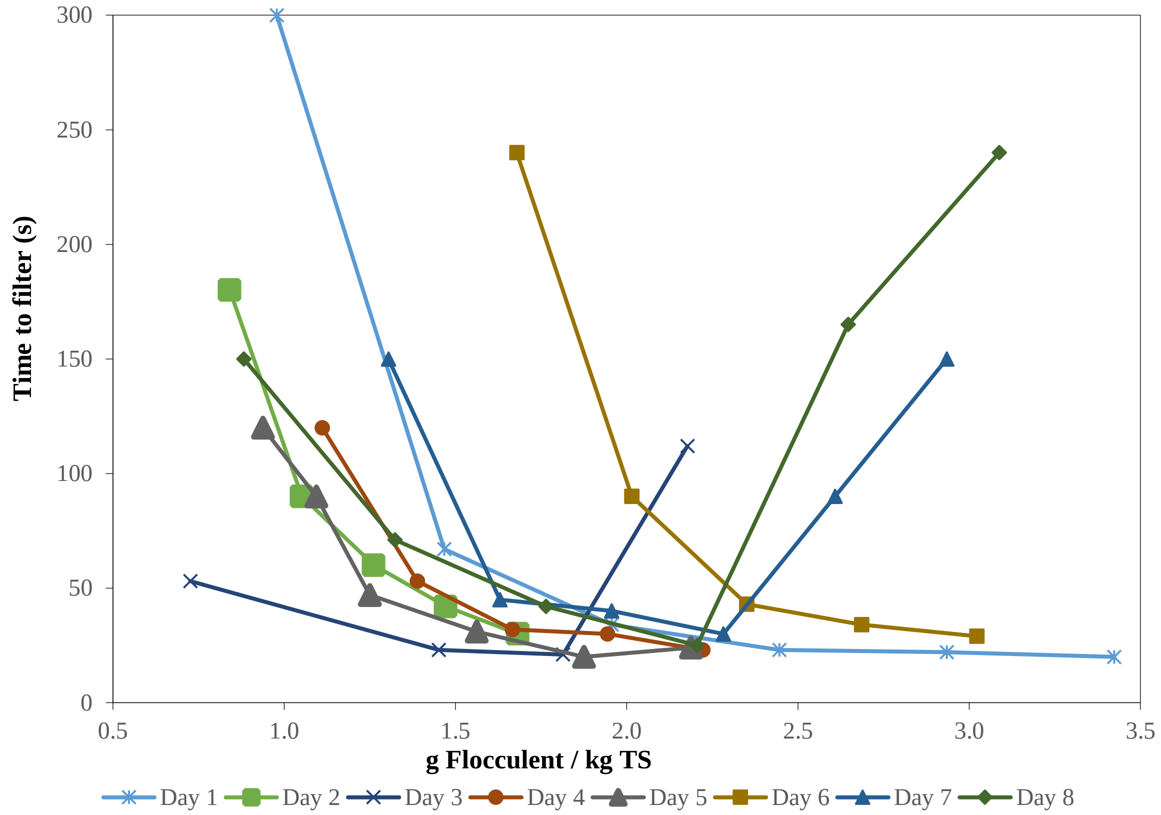


Figure 4.3 *Effect of flocculent dosage on dewaterability for TTF*

Table 4.2 was generated through evaluating behavior after minimum TTF of each day curve as shown in figure 4.3. Day 2,4, and 5 were varied with narrow flocculent dose ranges. Hence, it was not provided with enough evidence to make a conclusion about the behaviour of the curve after minimum TTF. Day 6 and day 3 recorded the highest turbidity (450 NTU) and lowest turbidity (150 NTU) in the supernatant of the influent respectively. Higher turbidity required higher flocculent dosage due to the higher surface area of colloids. Therefore, time to filter graph of day 6 remained nearly constant at the minimum time to filter value. However, day 3 time to filter graph showed an increasing trend after the minimum time to filter value, most likely due to the overdose of flocculent. Day 8 also observed an increasing trend after the minimum time to filter value due to the lower turbidity of supernatant (240 NTU) compared to the day 8 caused to the overdose of flocculent.

However, day 1 and day 7 curves behaved completely opposite to the above explanation. Day 1 had a lower turbidity of supernatant (220 NTU) and TS (0.92 %) compared to the day 7 turbidity of supernatant (400 NTU) and TS (1.39%). But day 1 curve remained constant after minimum TTF while day 7 showed increasing trend after minimum TTF. This could be possibly due to the influence of particle shape, chemical composition of sludge, and sludge compressibility on the dewaterability in addition to the particle size distribution(H.-F. Wang et al., 2020).

Dewaterability of the flocculated sludge was depended on several factors. Therefore, in full scale primary sludge thickening process would be more challenging to operate. The objectives of the thickening process should be achieved with lower flocculent dosage than flocculent dosage relevant to the minimum TTF of primary sludge. Otherwise, thickening process would not be favorable economically and operationally.

Table 4.2 *Effect of flocculent dosage after minimum TTF on 8 different days*

Day	**Each Curve Behavior after Minimum TTF**
1	remain consistent
2	unable to conclude
3	increasing trend
4	unable to conclude
5	unable to conclude
6	remain consistent
7	increasing trend
8	increasing trend

4.1.3 Filtrate Turbidity Test for Primary Sludge

Working principle of rotary drum thickener at SNJ WWTP is filtration. Therefore, flocculation of primary sludge and filtration step were combined and quality of filtrate was observed by this experiment. Figure 4.4 shows turbidity of the filtrate with respect to the increasing flocculent dosage on 8 different days. Turbidity of the primary sludge was above 4000 NTU. After flocculation and filtration steps, turbidity of the filtrate drastically reduced compared to the primary sludge turbidity. Higher flocculent dosage caused to lower the turbidity due to increase in capture efficiency of colloidal solids. However, sludge samples collected on different days required polymer dosage from 2-3 g flocculent/kg TS to achieve similar filter quality,

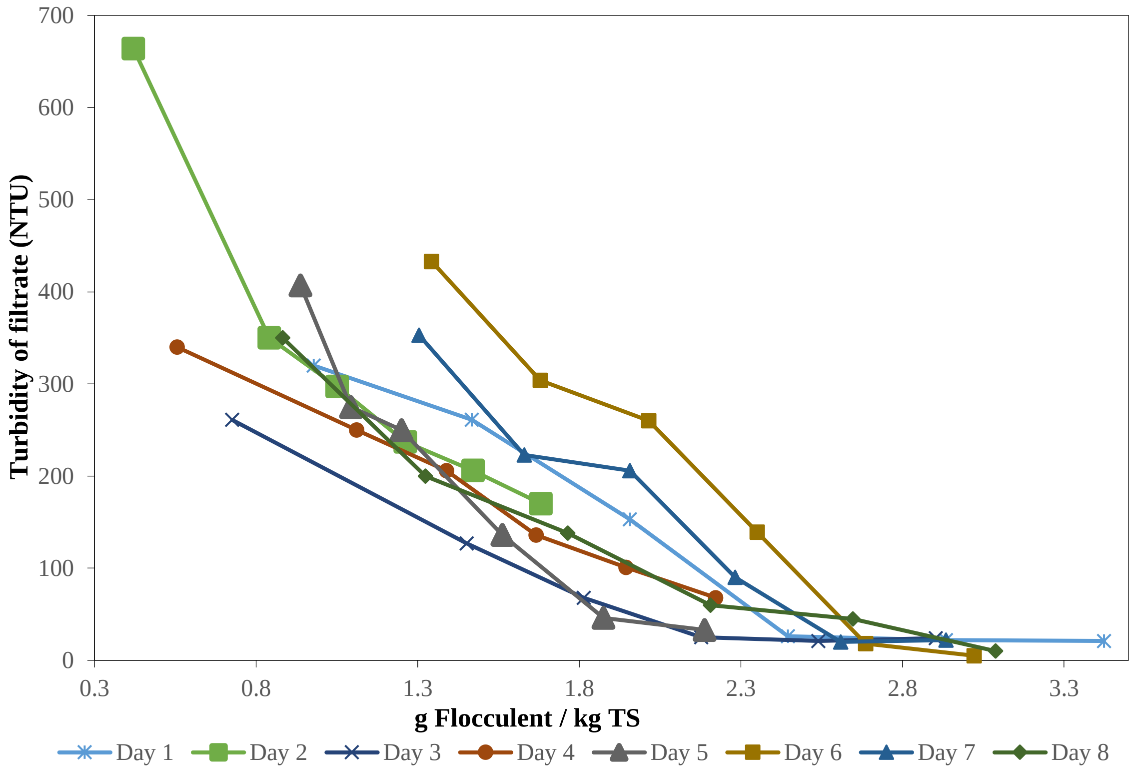


Figure 4.4 *Effect of flocculent dosage on turbidity of filtrate on 8 different days*

Flocculent dosage caused to change the turbidity of filtrate and time to filter of the primary sludge. These results indicate, turbidity of filtrate or time to filter are possible controlling parameters to control flocculent dosage of the primary sludge thickening process at full scale operation.

4.1.4 Factors Affecting Flocculation of Primary Sludge

The time to filter and turbidity of filtrate tests results were used to investigate the factors affecting flocculation. The flocculent dosages 1.3 g flocculent/kg TS were selected to analyze which characteristics of the primary sludge (TS, TSS, fatty acid, turbidity of supernatant, alkalinity and conductivity) mostly influenced the flocculation. Flocculent dosage (1.3 g flocculent/ kg TS) was selected by considering each day linear range of time to filter prior to the overdose of flocculent dosage.

Table 4.3 presents time to filter values and filtrate turbidity values corresponding to the 1.3 g flocculent/kg TS. All the values were obtained from figure 4.2 and 4.3.

Table 4.3 *TTF and Turbidity of filtrate at 1.3 g flocculent/ kg TS on 8 different days*

Day	**TTF (s)**	**Turbidity of Filtrate (NTU)**
1	130	290
2	60	230
3	30	150
4	70	220
5	40	230
6	430	450
7	150	350
8	70	200

4.1.4.1 Investigating the Effect of Influent TS and TSS on Flocculation

The effect of influent TS and TSS on flocculation were investigated with table 4.2 values which represented time to filter and turbidity of filtrate at flocculent dosage 1.3g /kg TS.
The figures 4.5a and 4.5b represents influent TS% and TSS variation respectively with the time to filter value on different 8 days and the figures 4.6a and 4.6b represents influent TS% and TSS variation respectively with the turbidity of filtrate on different 8 days. Due to the consistent TS to TSS ratio (0.77) correosponding time to filter figures(figure 4.5a and figure 4.5b)or turbidity of filtrate figures(4.6a and 4.6b) had similar pattern. The selected flocculent dosage (1.3 g flocculent/kg TS) determined the flocculent amount for the flocculation independent of the influent sludge load. If the time to filter or turbidity of filtrate was depended on influent sludge load, then, it was expected to achieve same time to filter value and turbidity of filtrate. However, according to the figures 4.5-4.6, the time to filter and turbidity of the filtrate varied considerably despite of the influent TS% and influent TSS. As a result it was suggested influent slugde load had lower impact on the flocculation.

However, figure 4.6 had some sort of increasing trend between turbidity of filtrate and influent TS or TSS compare to the figure 4.5. The correlation between influent TS and turbidity of supernatant was explained in section 4.1.1. There is a possibility to contain higher colloidal solids load in higher influent TS. Therefore, sludge samples which contained higher TS required higher flocculent dosage to aggregate most of the colloidal solids. Otherwise, turbidity of filtrate would increase at higher influent TS.

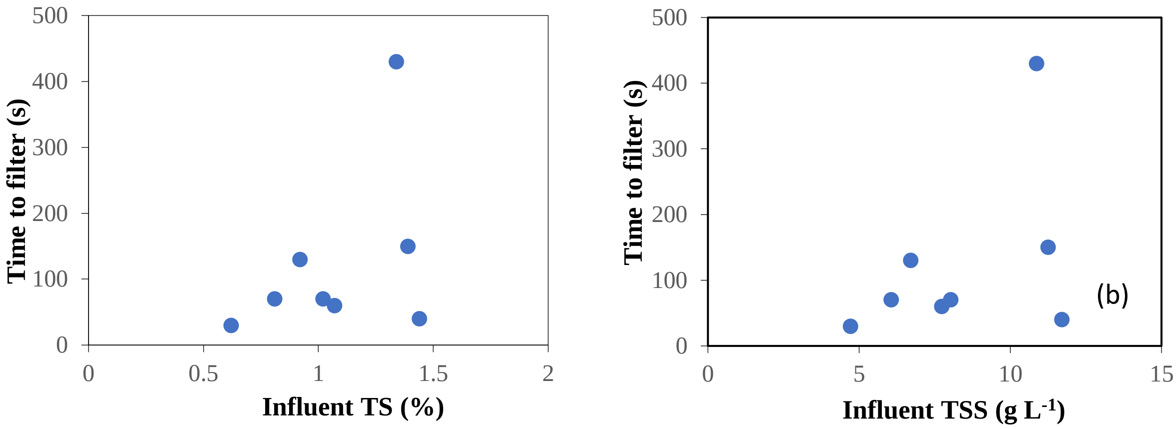


Figure 4.5 *Effect of influent (a)TS and (b)TSS on dewaterability for TTF*

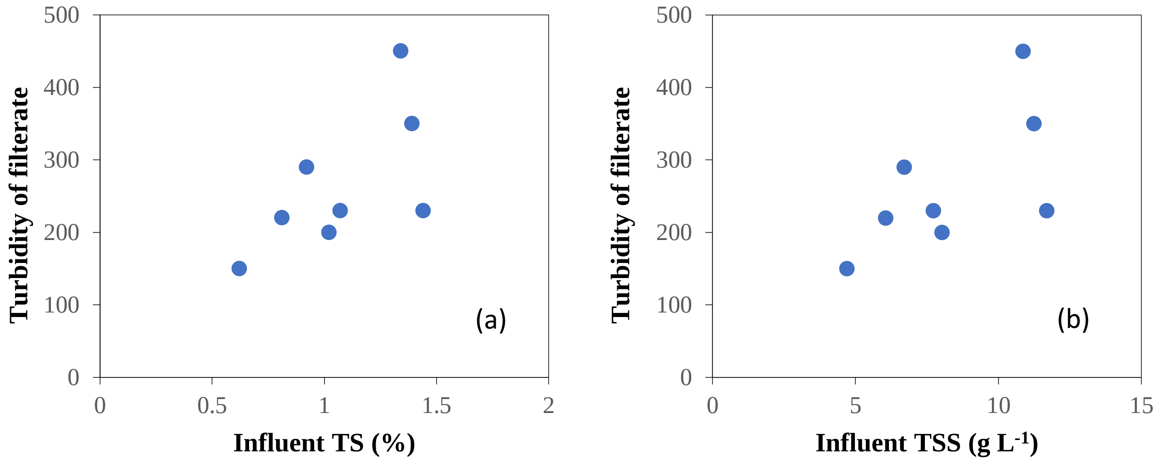


Figure 4.6 *Effect of influent (a)TS and (b)TSS on dewaterability for TTF*

4.1.4.2 Investigating the Effect of VFA and Turbidity of Supernatant on Flocculation

The effect of fatty acid content and turbidity of supernatant were investigated on time to filter value and turbidity of filtrate of the primary sludge. The figures 4.7a and 4.7b represent the fatty acid and turbidity of supernatant variation respectively with the time to filter value. When increasing both the factors, it resulted in an increasing time to filter value. This was due to the correlation between VFA and turbidity of supernatant that was explained under section 4.1.1. Turbidity of supernatant represented colloidal solids of the primary sludge. The fatty acid content did not affect the flocculation as it was a constituent of dissolved solids. However, VFA represented colloidal solids in the primary sludge. Hence, the higher VFA or turbidity of supernatant decreased the dewaterability of the primary sludge by increasing the time to filter. Both the highest fatty acid content (31.2 mg HAc L^{-1}) and turbidity of supernatant (450 NTU) resulted in the highest time to filter value (450 s). As well as the lowest fatty acid content (0.1

mg HAc L^{-1}) and turbidity of supernatant (150 NTU) resulted in the lowest time to filter value (30 s). However, linearity of both graphs was low. Hence, dewaterability was influenced by factors other than colloidal solids load.

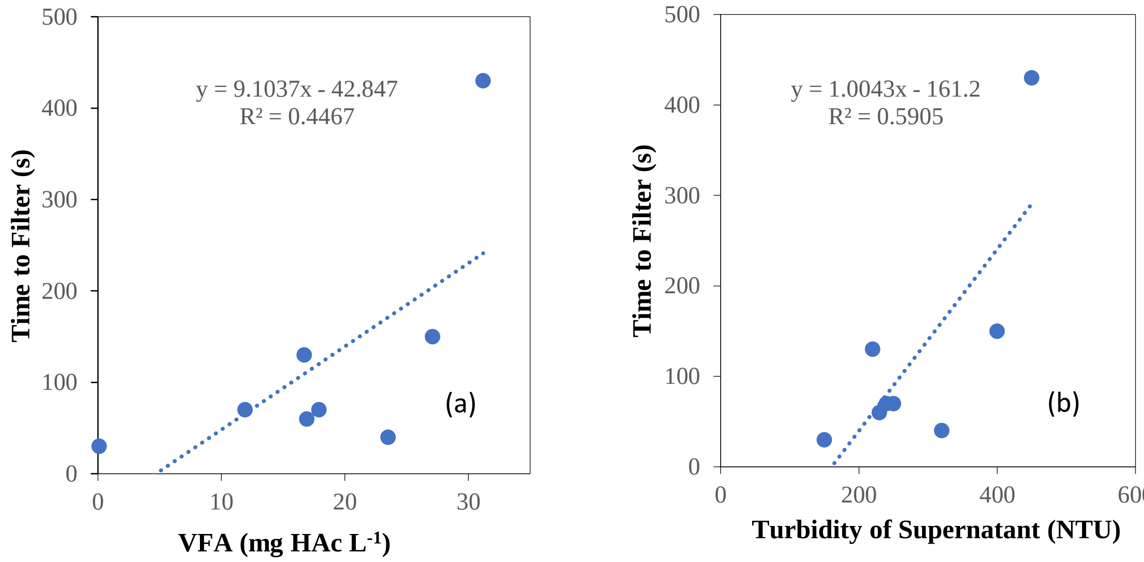


Figure 4.7 *Effect of influent (a) VFA and (b) Turbidity of supernatant on dewaterability for TTF*

The figures 4.8a and 4.8b represent the fatty acid content and turbidity of supernatant variation respectively with the turbidity of filtrate. The turbidity of filtrate indicates the quality of flocculation where a lower turbidity of filtrate indicates a higher capture efficiency of particles and vice versa. Both the figures 4.7a and 4.7b behaves similar to figures 4.8a and 4.8b respectively as it was discussed under it. The higher turbidity of the supernatant indicated the presence of higher colloidal solids which required a higher flocculent dosage.

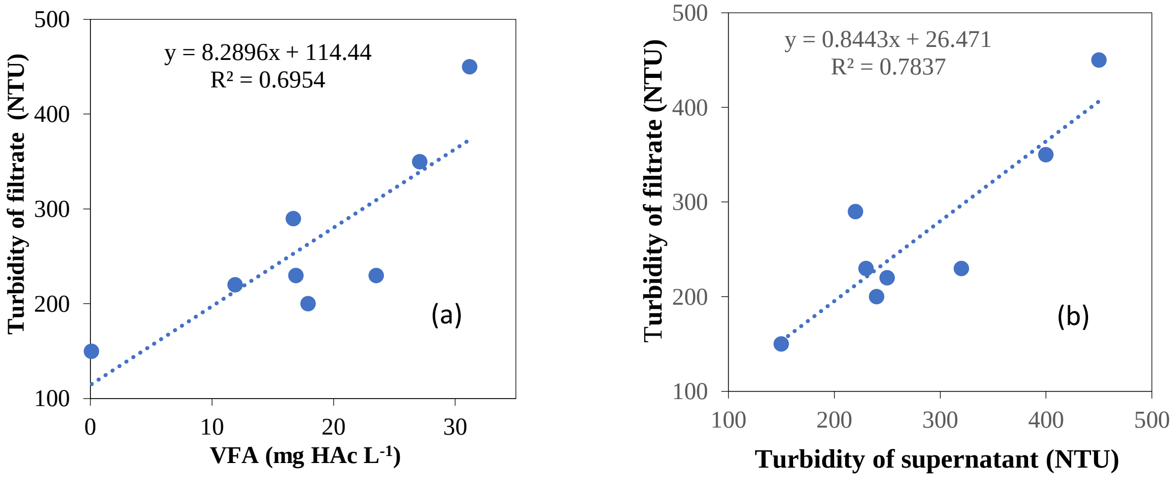


Figure 4.8 *Effect of influent (a)VFA and (b) Turbidity of supernatant on dewaterability for turbidity of filtrate*

When comparing the time to filter and turbidity of filtrate with the considered factors (fatty acid content and turbidity of the supernatant), the turbidity of filtrate had higher R^2 values indicating a more linear correlation with the factors compared to the time to filter value. Hence, time to filter which represented dewaterability of primary sludge was impacted by factors other than colloids solids load. However, higher R^2 values between turbidity of filtrate and turbidity of supernatant could suggest that quality of filtrate depended mostly on the particle size distribution in the primary sludge.

4.1.4.3 Investigating the Effect of Alkalinity and Conductivity on Flocculation

The effect of alkalinity and conductivity of primay sludge were investigated on time to filter value and turbidity of filtrate of the primary sludge. The figures 4.9a and 4.9b represent the alkalinity and conductivity variation respectively with the time to filter value and the figures 4.10a and 4.10b represent alkalinity and conductivity variation respectively with the turbidity of filtrate. According to the figures there were not enough evidence to establish correlation between flocculation and alkalinity or conductivity. However, two factors (septicity and seawater concentration) were identified for conductivity variation in the influent of SNJ WWTP, which were discussed under section 4.1.1. Septicity was resulted to increase the conductivity and colloidal solids. Higher colloidal solids resulted a decrease in dewaterability of primary sludge.

Sea water caused an increase in conductivity and dewaterability. High salinity has an impact to lower the swelling pressure of the flocs by shifting Donnan equilibrium between flocs and water. As a result, the force retaining the "trapped" water in the sludge flocs is decreased and the dewaterability is increased (Remmen et al., 2017).

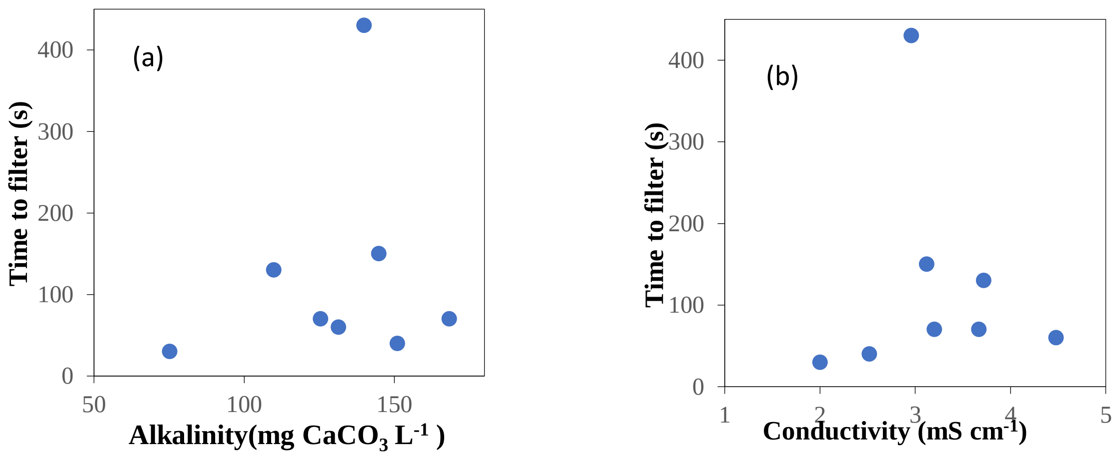


Figure 4.9 *Effect of influent (a)Alkalinity and (b) Conductivity on dewaterability for TTF*

In conclusion, conductivity caused by septic sludge would result in decreasing dewaterability due to higher colloids in the sludge and, conductivity caused by seawater would result in increasing dewaterability. Therefore, dewaterability of sludge can be explained only after understanding which factor affected the conductivity mostly.

Comparison between figure 4.2 and figure 4.10b explained that the sludge which had the highest VFA of 31.2 mg HAc L^{-1} which represented highest colloidal solids load resulted in a conductivity around 3.0 mS cm^{-1} and the highest time to filter value(450s). The highest conductivity (4.5 mS cm^{-1}) had a lower VFA concentration of 16.9 mg HAc L^{-1} but a lower time to filter value. Hence the highest conductivity may be caused by sea water resulting in a higher dewaterability.

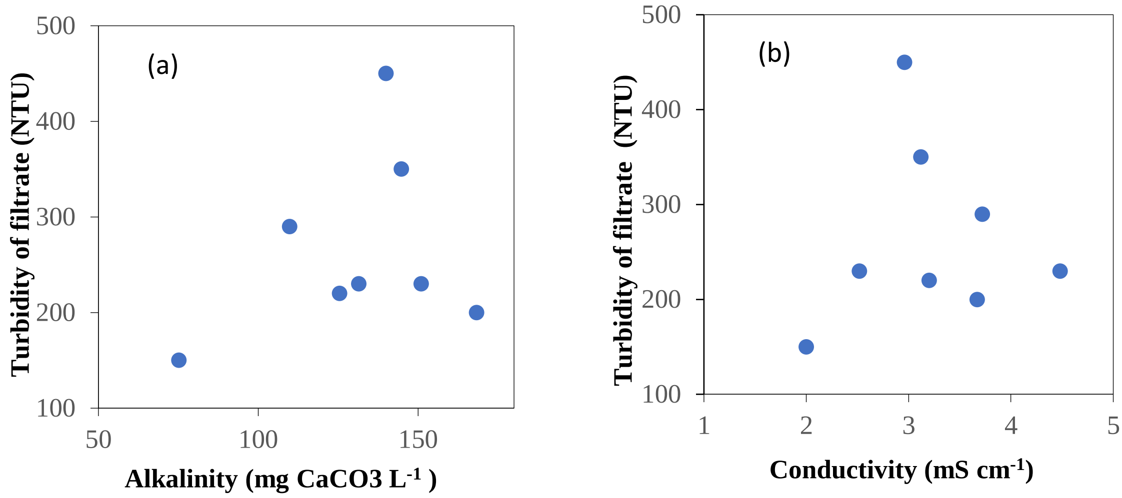


Figure 4.10 *Effect of influent (a)Alkalinity and (b) Conductivity on dewaterability for turbidity of filtrate*

4.1.5 Flocculation Test for Mixed Sludge

The objective of this experiment is to understand whether it is possible to obtain nearly constant dewaterability with fixed flocculent dosage if primary sludge is mixed with secondary sludge. The table 4.4 shows the TS and optimum flocculent dosage for primary sludge and biological sludge for 3 days. The flocculent dosage for the biological sludge was higher than the flocculent dosage for the primary sludge due to the higher fraction of colloidal solids in the biological sludge (Meyer et al., 2018). The flocculent dosage variation of the primary sludge was significantly higher than the variation of flocculent dosage for the biological sludge. This can be to the particle distribution range is higher in primary sludge compared to the biological sludge (Meyer et al., 2018).

Table 4.4 *Primary and secondary sludge TS and optimum flocculent dosage on day 9,10 and 11*

Day	TS % of Primary Sludge	TS % of Biological Sludge	Optimum Flocculent Volume for Primary Sludge of 200 mL (mL)	Optimum Flocculent Volume for Secondary Sludge of 200 mL (mL)
9	0.75	2.06	3	15
10	1.08	2.1	6	16
11	1.05	2.34	7	18

Figure 4.11 shows time to filter variation with respect to the flocculent dosage of each mixed sludge for 3 days. Time to filter values at a particular flocculent dosage varied each day. A larger fraction of mixed sludge was primary sludge and characteristics of it (solids fraction) varied significantly compared to the biological sludge. Therefore, it was not possible to obtain fixed dewaterability for mixed sludge.

Flocculent dosage of mixed sludge sample was determined by mixed sludge ratio and optimum flocculent dosages of primary and secondary sludge. Secondary sludge to primary sludge ratio of 1: 9 represented the lowest flocculent dosage for each day. When increasing secondary sludge fraction in mixed sludge, flocculent dosage was increased. Therefore, highest flocculent dosage was represented when the secondary to primary sludge ratio is 1:1. However, there was an increasing trend in time to filter value when secondary fraction in mixed sludge increased, even though flocculent dosage increased. This was due to the higher colloidal fraction in the secondary sludge(Meyer et al., 2018).

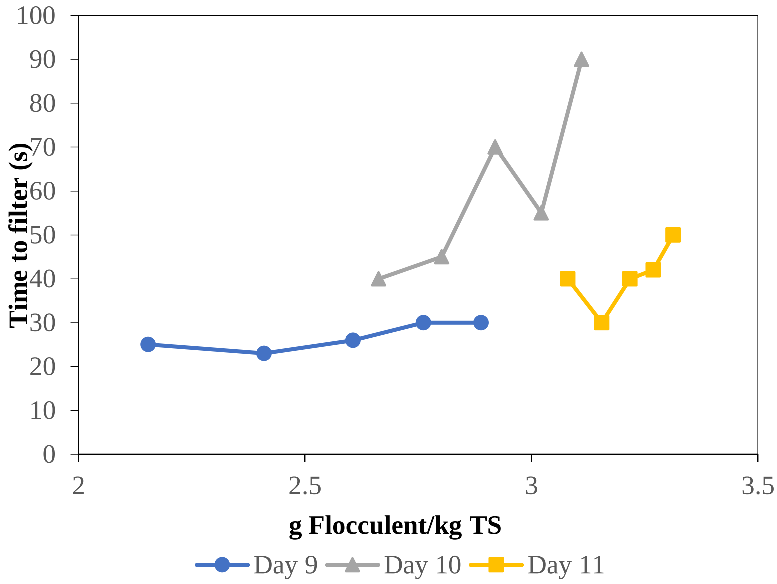


Figure 4.11 *Effect of flocculent dosage on TTF of mixed sludge on 3 different days*

Therefore, dewaterability also changed with secondary to primary sludge ratio. The influence of primary sludge on dewatering of mixed sludge was investigated by other authors. Meyer et al. (2018) reported that the primary sludge acts as the component that decreases compressibility of bio-sludge. Therefore, dewaterability was increased when primary sludge fraction increased. Hence, it was not recommended to thicken the mixed sludge with a fixed flocculent dosage due to the higher primary sludge fraction and variation of secondary to primary sludge ratio.

4.2 Full-scale Experiments with Rotary Drum Thickener

This sub chapter is further divided into four sections in order to explain effect of operation parameters to the thickening process at SNJ WWTP. The operational parameters are flocculation reactor mixing speed, rotational speed of thickener, backwash mechanism, and flocculent dosage.

4.2.1 Flocculation Reactor Mixing Speed

Mixing and reaction stages of flocculation occurred within static mixer and flocculator mixer respectively at SNJ WWTP. The typical ranges of velocity gradient and retention time that have been used for flocculation in direct filtration process were reported as 25 -150 s^{-1} and 2-10 minutes respectively (Tchobanoglous et al., 2014). The velocity gradient (G) and retention time of the flocculator mixer at SNJ WWTP were 254.75 s^{-1} and 0.48 minutes respectively and were beyond the typical range of flocculator. The G and retention time were calculated. at 65 $m^3\ h^{-1}$ and included in Appendix 4.4.

Table 4.5 shows characteristics of the primary sludge which were collected on day 2, 4 and 24. The figures 4.12a-4.12c represent time to filter measurements conducted with influent flowrates of 45 $m^3\ h^{-1}$, 55 m^3h^{-1}, and 65 m^3h^{-1} when mixer was on and off on three different (day 2, 4 and 24) respectively. Flocculent dosage was fixed on each day independent of the flowrate variation.

Table 4.5 *Characteristics of primary sludge on day 2, 4, and 24*

Day	TS %	TSS ($g\ L^{-1}$)	Turbidity of Supernatant (NTU)
2	1.07	7.73	230
4	0.81	6.06	250
24	1.4	13.375	480

Flocculator tank was smaller (0.52 m^3) compared to the influent flow. As a result, it created turbulence in addition to the flocculator mixer. The turbulence created by the influent flow may be sufficient to provide better flocculation. In such case, turbulence produced by the flocculator mixer caused floc rupture due to high G value (Balemans et al., 2020; Mohammed and Shakir, 2018).when influent flowrate reduced from 65 $m^3 h^{-1}$ to 45 $m^3 h^{-1}$, the retention time of the flocculator mixer was increased from 0.48 minutes to 0.7 minutes. Therefore, sludge particles had more time to aggregate and obtained better dewaterability.

In all tests the time to filter value changed when the mechanical mixer was turned off. Day 2 and 24 received lower time to filter, in other words better dewaterability when flocculator mixer was turned off. However, day 4 received better dewaterability with flocculator mixer. Minimum influent TS was recorded on day 4 which was 0.81%. Therefore, the requirement of mixer was depended on the influent sludge load. When influent TS was greater than 1 %, turbulence created by flow and tank geometry was enough to aggregate particles and produced a better dewaterability of sludge. However, a flocculator mixer was required in order to produce more turbulence for aggregation of particles when influent TS was less than 0.8%. Such operation was economically favorable due to lower flocculent requirement in order to achieve required dewaterability.

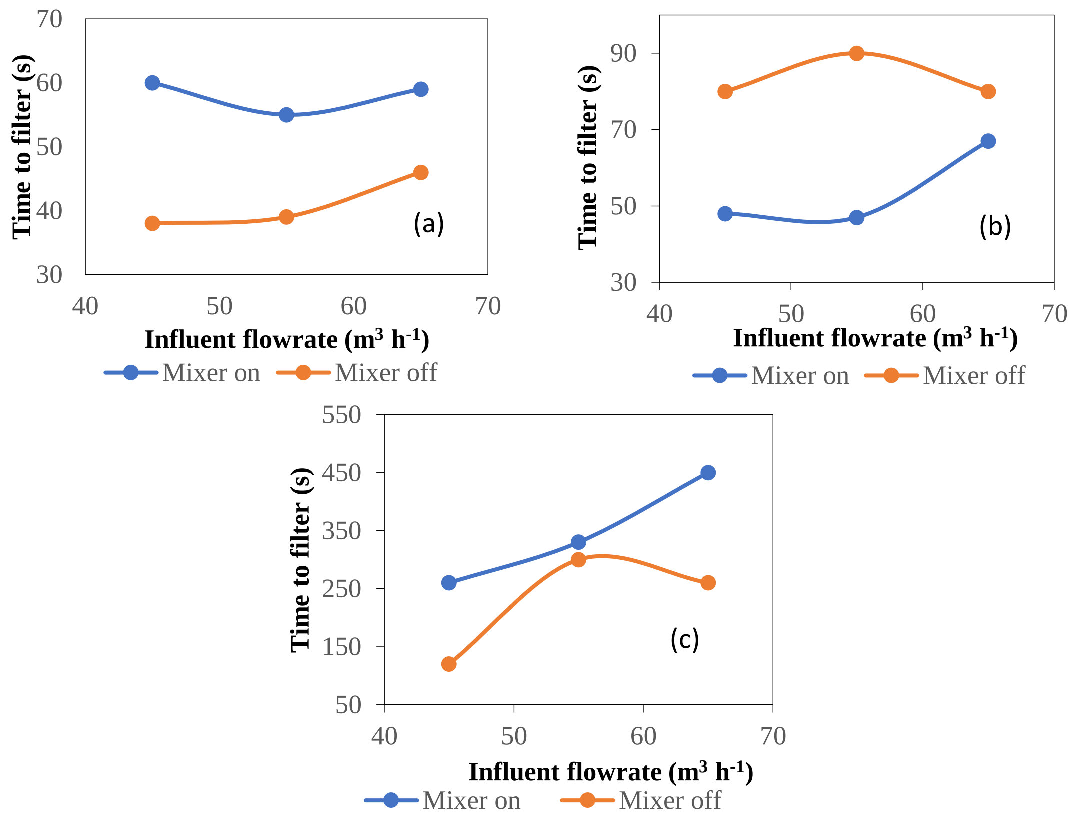


Figure 4.12 *Effect of flocculator mixer on TTF at influent flowrates 45 $m^3 h^{-1}$,55 $m^3 h^{-1}$,and 65 $m^3 h^{-1}$on day (a)2,(b)4.and (c)24*

4.2.2 Rotational Speed of Drum Filter

Rotational speed of rotary drum thickener can be varied through four different stages which are 1.6 rpm, 3.2 rpm, 4.8 rpm and 6.4 rpm. The objective of this experiment is to investigate whether it is possible to obtain 5 ±1% of TS from effluent for every sludge influent only by varying the rotational speed of thickener.

Figure 4.13 describes effluent TS with the rotation speed of thickener for day 16,22, and 23. At 1.6 rpm, the lowest effluent TS was observed even though sludge had highest HRT. The moving speed of sludge within the drum was slow at lower rpm which caused to produce concentrated sludge. However, influent of thickener had higher speed compared to the sludge moving speed within the drum. Therefore, influent sludge reached to the effluent without reasonable filtration. This caused to create 2 layers within the drum at 1.6 rpm as shown in figure 4.14. Effluent TS% at 1.6 rpm was resulted by concentrated sludge and non-filtered sludge.

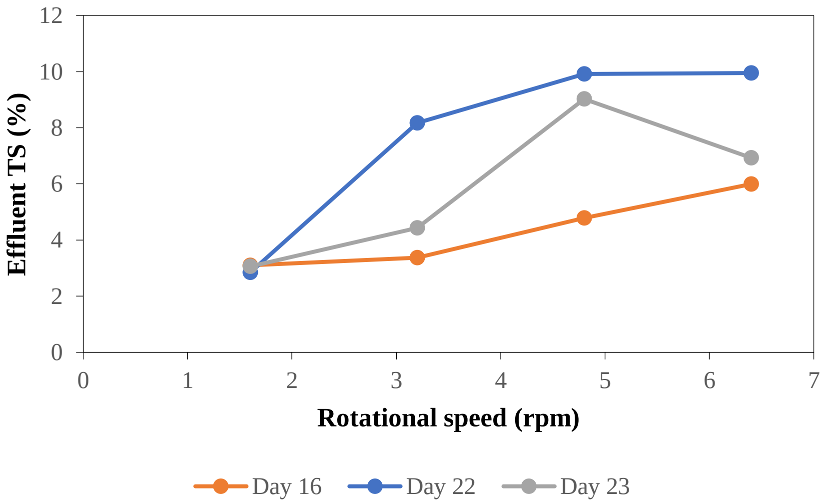


Figure 4.13 *Effect of rotational speed f thickener to the effluent TS on day 16, 22, and 23*

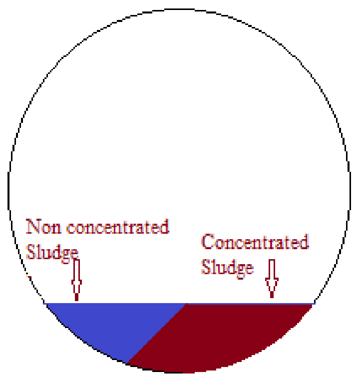


Figure 4.14 *Schematic diagram of inside the drum thickener when rotational speed of thickener at 1.6 rpm*

Table 4.6 shows minimum time required to clean whole drum filter at different rotational speed of the thickener. At 1.6 rpm, backwash time period (20 s) was not enough to clean whole drum filter. As a result, particles could clog the filter. This caused to reduce filtration capacity. That was a possible reason to reduce effluent TS significantly at 1.6 rpm.

Table 4.6 *Current backwash method and minimum time required to clean whole filter at different rotational speed of thickener*

Rotational Speed of Thickener (RPM)	Time Required to Clean Whole filter (s)	Backwash Mechanism; Backwash (s) /Pause (s)
1.6	38	20/10
3.2	19	
4.8	12.5	
6.4	9	

When increasing rotation speed from 1.6 rpm, the fraction of influent sludge reached to the effluent without reasonable filtration was reduced. At the same time, higher rpm caused a reduced HRT. However, reduction of non-filtered fraction (non-concentrated sludge) in effluent caused to increase the TS% in the effluent. Day 22 and 23 received the highest TS% in the effluent at 4.8 rpm. Therefore, optimum rotational speed for primary sludge can be considered as 4.8 rpm. Because, the lowest flocculent dosage was required when thickener operated at optimum rotational speed. When further increasing the rotational speed, all the influent sludge received was filtered before reaching the effluent but it had the lowest HRT which caused to decrease the effluent TS.

Effluent TS% on day 22 was increased from 2.8 % to 8.2% when rotational speed increased from 1.6 rpm to 3.2 rpm. As a result, it was not possible to obtain effluent TS 5±1 % on day 22. In conclusion, effluent TS 5±1 % was not able to be obtained only by changing the rotational speed of the thickener.

4.2.3 Backwash Mechanism

This experiment was operated at optimum rotational speed (4.8 rpm) of the thickener. Figure 4.15 illustrates the effluent TS% with time after stopping backwash operation for day 24 and 25. Backwash operation was needed to clean the perforated filter in order to maintain effective filtration. According to the figure 4.15, effluent TS% was significantly reduced after 1 minute. It was due to the clogging of filter by sludge particles, which lead to reduce the filtration capacity. Therefore, the maximum time between two backwash cycles in the thickener operation should be 1 minute. As well as minimum 12 seconds was required to clean the whole drum filter at optimum rotational speed (4.8 rpm).

Cripps and Bergheim, (2000) proposed warm water can be used for backwashing when sludge contains larger fraction of fats. And sea water is another alternative for backwashing when filtrate of thickener is discharged to the marine environment. Filtrate of thickening process at SNJ WWTP is moved to the marine environment, but due to the flocculation step warm water would be a better option for backwashing.

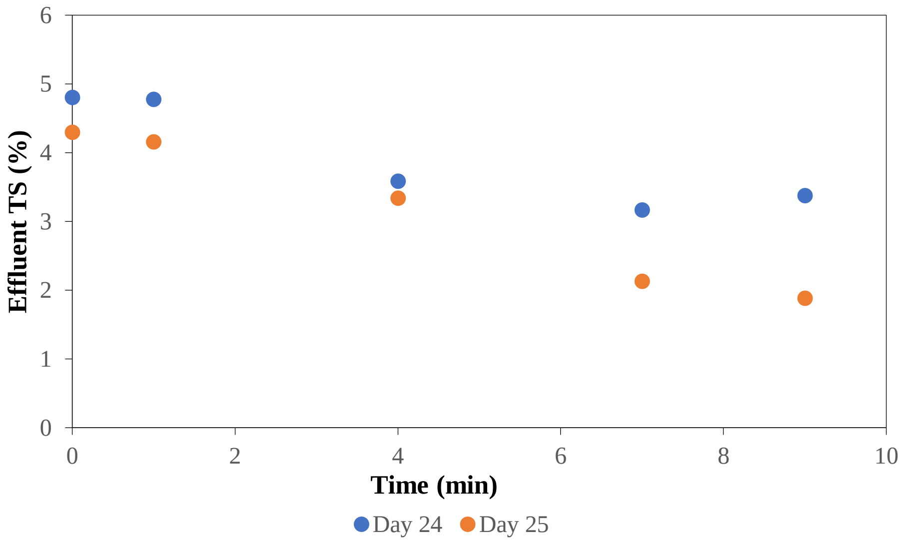


Figure 4.15 *Effect of pause time period of backwashing mechanism on effluent TS at day 24 and 25*

4.2.4 Flocculent Dosage

The effect of flocculent dosage on the thickening process was analyzed through effluent TS, turbidity of filtrate and time to filter value of influent of the thickener. The table 4.7 represents the characteristics of primary sludge (TS , TSS, turbidity of supernatant and conductivity) under different flowrates (50 m^3h^{-1}, 65 m^3h^{-1}, 71 m^3h^{-1}) on 11 different days. The usual operational flowrate range of the thickening process was 50- 75 m^3h^{-1} but due to an operational issue of the primary sludge pump, only a maximum flowrate of 71 m^3h^{-1} could be obtained. Samples were collected before and after conducting the experiment and their mean TS and TSS values were recorded. A t-distribution analysis with 90% certainty was used to determine errors of the TS and TSS.

Table 4.7 *Primary sludge flowrates and characteristics on different 11 days*

Day	**Influent Flowrates (m^3h^{-1})**	**TS %**	**TSS (mg mL^{-1})**	**Turbidity of Supernatant (NTU)**	**Conductivity (mS cm^{-1})**
12	50	1.22±0.11	9.75±0.49	590	2.3
13	50	1.03±0.09	7.44±1.02	280	4.3
14	50,65	1.14±0.06	8.81±0.62	160	4.4
15	50	1.14±0.02	9.45±0.76	230	1.8
16	50,71	1.14±0.08	9.91±0.74	420	1.8
17	65	1.24±0.02	10.30±0.61	390	3.6
18	65	1.23±0.03	9.88±0.29	370	3.3
19	65	1.3±0.06	10.71±0.99	450	3.1
20	65	0.77±0.03	5.61±0.43	130	3.4
21	71	1.37±0.12	10.41±0.47	250	3.4
22	71	1.02±0.54	9.11±0.54	180	2.4

4.2.4.1 Effect of Flocculent dosage on Effluent TS of the thickener

The figures 4.16a, 4.17a and 4.18a represent effluent TS variation with the g flocculent / kgTS at an influent flow rate of 50 m^3h^{-1}, 65 m^3h^{-1} and 71 m^3h^{-1} respectively. The figures 4.16b, 4.17b and 4.18b represents effluent TS% variation with the g flocculent / kgTSS at a influent flow rate of 50 m^3h^{-1}, 65 m^3h^{-1} and 71 m^3h^{-1} respectively. The effluent TS% showed an increasing trend with respect to g flocculent / kgTS and g flocculent / kgTSS in figures 4.15 to 4.18 because higher flocculent dosage resulted flocs with a higher dewaterability.

A better correlation could be observed between effluent TS and g flocculent / kgTS compared to g flocculent / kgTSS in all the days where turbidity was greater than 200 NTU. This was due to the error created by the absence of colloidal solids in TSS which was more significant than the error due to the presence of dissolved solids in TS. The dissolved solids in primary sludge were usually very low because a higher proportion of dissolved solids moved to the biological treatment after rotary drum filter.

The day 14 in figures 4.16a and 4.16b required a lower flocculent dosage compared to the other days to reach a 5% effluent TS. The day 14 had the lowest turbidity (160 NTU). Hence, it had the lowest colloidal solid fraction. Also, its sludge had a lower septicity. When the turbidity was greater than 200 NTU and lower than 200 NTU, a flocculent dosage of 0.9-1.0 g flocculent / kg TS and 0.5 g flocculent / kg TSS respectively was required to achieve a 5% TS in effluent.

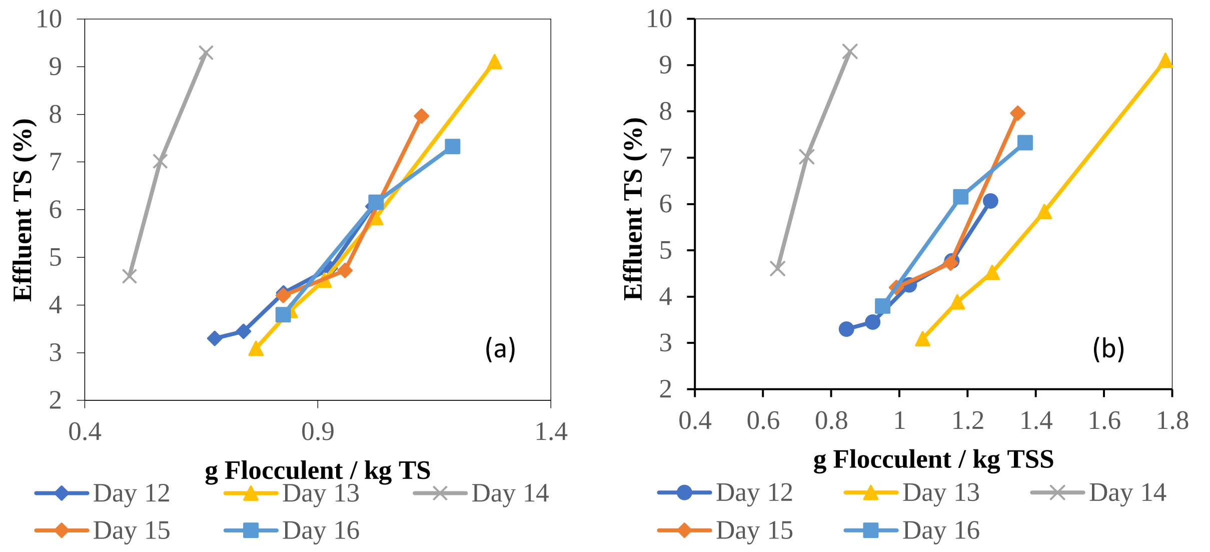


***Figure 4.16** Effect of flocculent dosage on effluent TS at 50 m^3 h^{-1};(a) g flocculent/kg TS, (b) g flocculent/kg TSS*

The day 14 and day 20 in figures 4.17a and 4.17b required a lower flocculent dosage compared to the other days to reach a 5% effluent TS. The day 14 and day 20 had the lower turbidities of 160 NTU and 130 NTU respectively. Hence, they had lower colloidal solid fractions. Also, their sludge had a lower septicity. The day 14 had a higher conductivity (4.4 mS cm^{-1}) compared to conductivity (3.4 mS cm^{-1}) of day 20 which was possibly due to the impact of sea water on day 14. Therefore, the required flocculent dosage in day 14 was further reduced compared to day 20. The flocculent dosage of 1.2-1.3 g flocculent / kg TS was required to achieve a 5% TS in effluent when the turbidity was greater than 200 NTU. Although, when turbidity of supernatant was lower than 200 NTU, the flocculent dosage of 0.8-0.9 g flocculent / kg TS was required to achieve a similar effluent solid concentration.

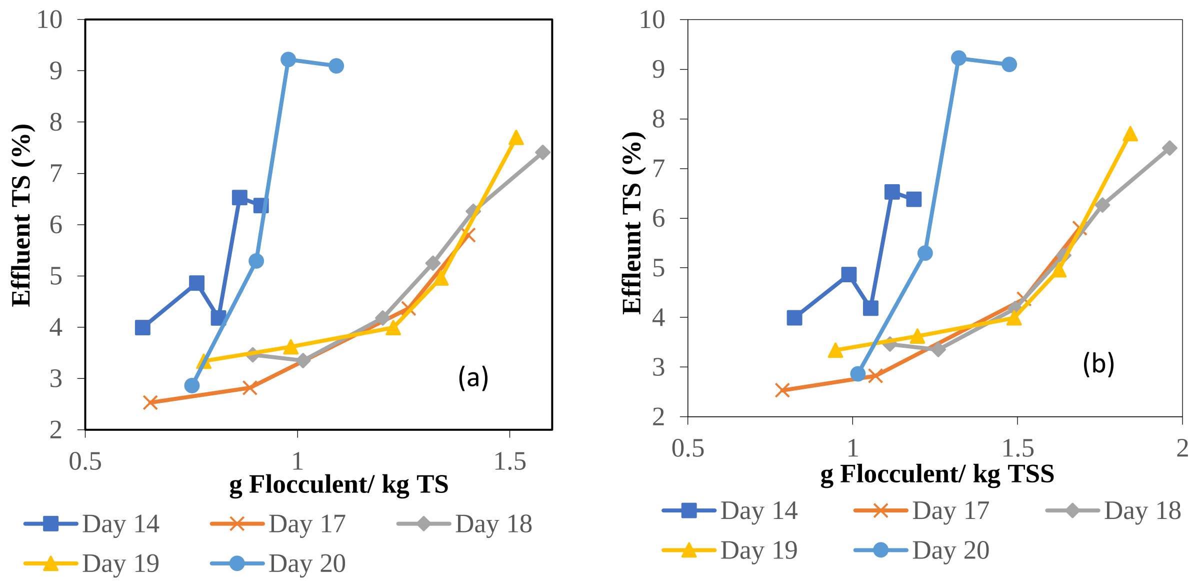


***Figure 4.17** Effect of flocculent dosage on effluent TS at 65 m^3 h^{-1};(a) g flocculent/kg TS, (b) g flocculent/kg TSS*

The day 22 in figures 4.18a and 4.18b required a lower flocculent dosage compared to the other days to reach a 5% effluent TS. The day 22 had the lowest turbidity (180 NTU). Hence, it had the lowest colloidal solid fraction. Also, its sludge had a lower septicity. When the turbidity was greater than 200 NTU and lower than 200 NTU, a flocculent dosage of 1.2-1.3 g flocculent / kg TS and 1.1 g flocculent / kg TS respectively was required to achieve a 5% TS in effluent.

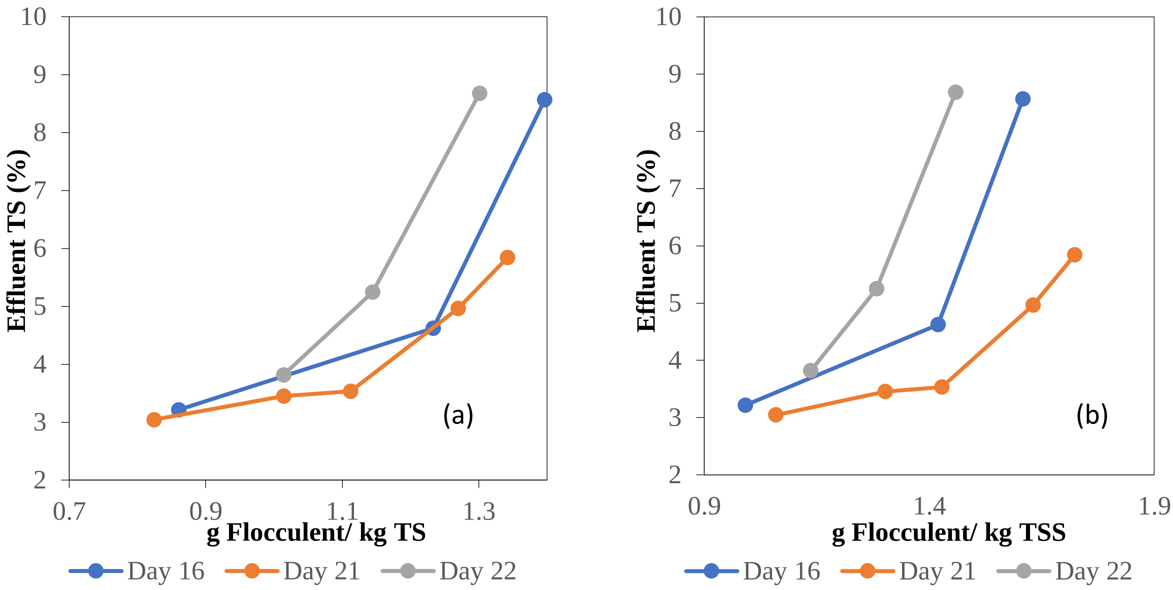


Figure 4.18 *Effect of flocculent dosage on effluent TS at 71 m^3 h^{-1};(a) g flocculent/kg TS, (b) g flocculent/kg TSS*

The HRT values of drum thickener at influent flowrates 50 m^3h^{-1}, 65 m^3h^{-1}, and 71 m^3h^{-1} were 2 minutes, 1.5 minutes, and 1.4 minutes respectively (Appendix 4.6). When the influent flow rate increased, the HRT values decreased. Therefore, in order to obtain 5 % of TS in sludge, dewaterability of the flocculated sludge should be increased by adding a higher flocculent dosage at higher influent flowrate. This was observed by the experimental results from the figures 4.13 to 4.15.

Overall, effluent TS% can be easily changed by varying flocculent dosage. Therefore, it is the perfectly manipulated variable in order to control the thickening process.

4.2.4.2 Effect of Flocculent Dosage on Time to Filter and Filtrate Turbidity

The figures 4.19 represents time to filter of influent to the thickener and turbidity of filtrate variation with increasing flocculent dosage at an influent flow rate of 50 m^3h^{-1}. Time to filter of influent to the thickener was measured on three different days while turbidity of filtrate was measured on five different days. The time to filter values, which were greater than 300 seconds, were not considered when plotting the graphs because it resulted in too lower dewaterability. During laboratory scale experiments, effect of flocculent dosage on time to filter and turbidity of filtrate were observed. All the figures, (full scale and lab scale) had similar trend where, time to filter and turbidity of filtrate had inverse relationship with respect to the flocculent dosage due to aggregation of colloidal solids to the flocs and increased size of flocs. However, laboratory scale experiments were conducted with higher flocculent dosage range compared to the full-scale experiments. Therefore, overdose of flocculent dosage (time to filter value was increased after minimum time to filter value) was not observed in full-scale experiments.

According to the figure 4.19, day 12 required higher flocculent dosage to obtain specific time to filter value or filtrate turbidity compared to the day 14. This was due to the difference between turbidity in supernatant of influent on day 12 (590 NTU) and day 14(160 NTU).

Similar relationship was observed between flocculent dosage and time to filter of influent to the thickener or turbidity of filtrate at influent flowrate 65 $m^3 h^{-1}$ and 71 $m^3 h^{-1}$. Hence, those figures were included in Appendix 4.7.

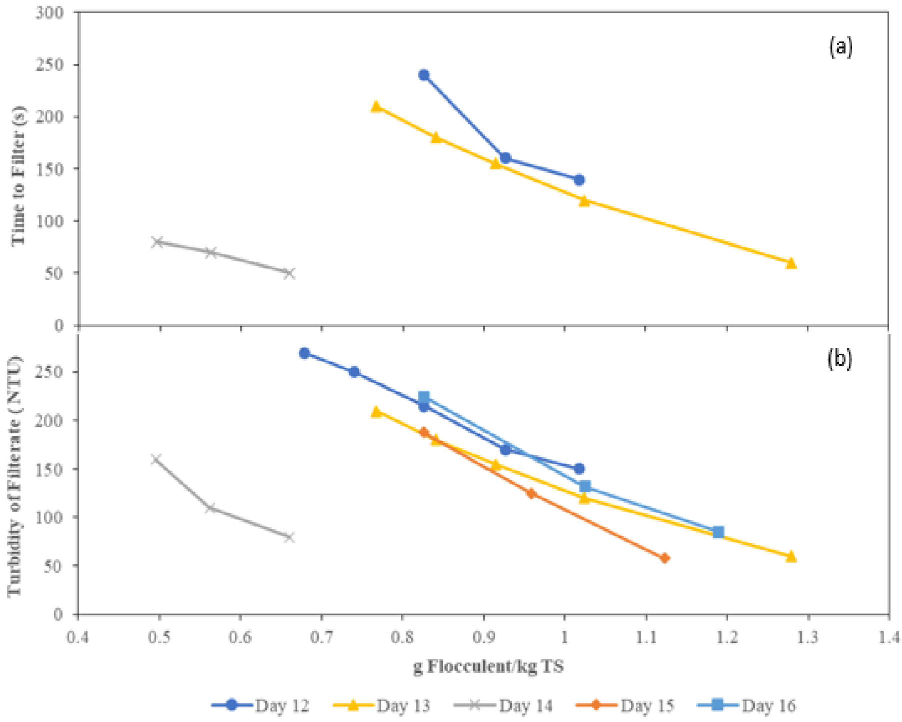


Figure 4.19 *Effect of flocculent dosage on ;(a) TTF, (b) Turbidity of filtrate at 50* m^3h^{-1}.

Overall, time to filter and turbidity of filtrate were varied in measurable range when flocculent dosage was changed. Therefore, thickening process can be controlled by time to filter and turbidity of filtrate as control variables to manipulate flocculent dosage.

4.3 Feedback and Feedforward Controlling Parameters for Thickening Process

From the lab and full-scale experiments flocculent dosage was identified as main manipulated variable to control effluent TS in the primary sludge thickening process. Under this chapter, possible feedback and feedforward parameters were discussed. Possible Feedback parameters were identified as time to filter of flocculated sludge, turbidity of filtrate, and flowrate of filtrate. As well as influent TS, TSS, turbidity, flowrate were identified as possible feedforward parameters.

4.3.1 Time to Filter and Turbidity of Filtrate

The inverse correlation between time to filter or turbidity of filtrate with flocculent dosage and positive correlation between effluent TS% and flocculent dosage were already recognized under flocculation dosage section. As a summary of that section, figures 4.20a, 4.21a and 4.22a represent effluent TS% variation with the turbidity of filtrate at an influent flow rate of 50 m^3h^{-1}, 65 m^3h^{-1} and 71 m^3h^{-1} respectively. The figures 4.20b, 4.21b and 4.22b represent effluent TS% variation with the time to filter of flocculated sludge at an influent flow rate of 50 m^3h^{-1}, 65 m^3h^{-1} and 71 m^3h^{-1} respectively. Effluent TS% had inverse correlation with time to filter and turbidity of filtrate. As described earlier, lower time to filter or turbidity of filtrate represented higher dewaterability of flocculated sludge. Therefore, most of the influent sludge load moved to the effluent and which contained in a low volume caused to increase effluent TS%.

According to the figures 4.20b and 4.21b, time to filter values at each day varied significantly at effluent TS 5%. However, similar time to filter value was expected due to the fixed HRT of the thickener but the influent TS% can change the time to filter value. Higher influent TS required lower dewaterability (higher TTF value) to obtain effluent 5% of TS. In the figure 4.20b, the time to filter value to obtain 5% TS on day 12 (160 seconds) and day 14(80 seconds) were significantly different even though influent TS was 1.22 % and 1.14 % respectively.

Similar behavior had been observed in figure 4.21b. Therefore, dewaterability of flocculated primary sludge was not only depended on the solids load in primary sludge. The physical operation (the rotational movement of the sludge towards the outlet) within rotary drum thickener influenced the variation in dewaterability of the flocculated sludge because of change in compressibility of sludge, floc size, and floc geometry (H.-F. Wang et al., 2020).

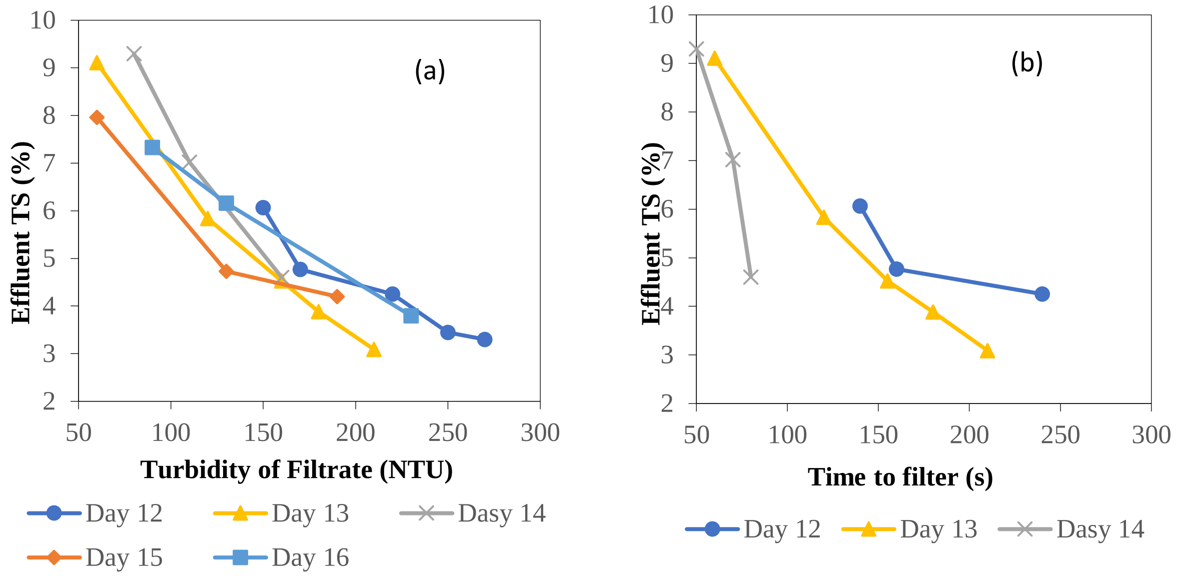


Figure 4.20 *The relationship between effluent TS and (a) Turbidity of filtrate and (b) TTF at flowrate 50 m^3h^{-1}*

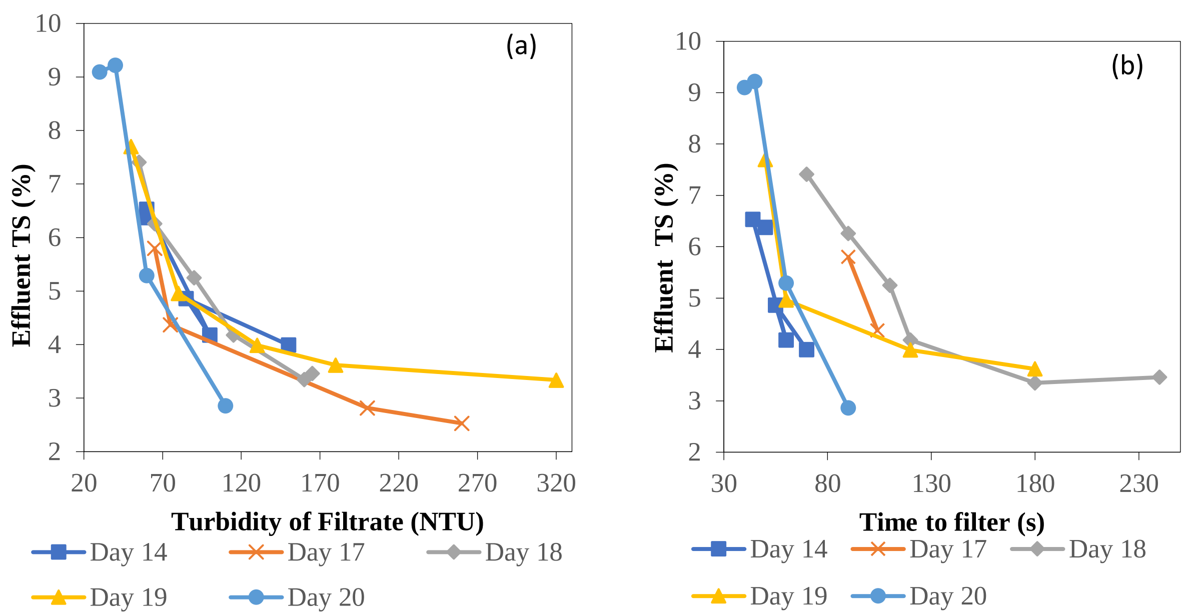
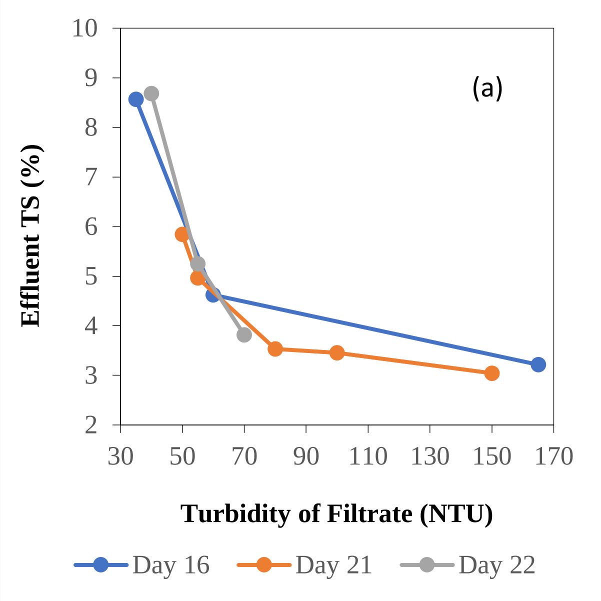


Figure 4.21 *The relationship between effluent TS and (a) Turbidity of filtrate and (b) TTF at flowrate 65 m^3h^{-1}*

A positive correlation between the turbidity of filtrate and the time to filter can be observed by comparing the corresponding figures at the same influent flowrate. Turbidity of filtrate can be correlated to the TSS or TS. In fact, higher TSS or TS in filtrate indicated lower dewaterability of flocculated sludge. A similar phenomena had also been reported in the literature by Cobbledick et al., (2017), The result revealed that TSS in filtrate had strong correlation with dewaterability. Therefore, online turbidity measurements can be used to control thickening process.



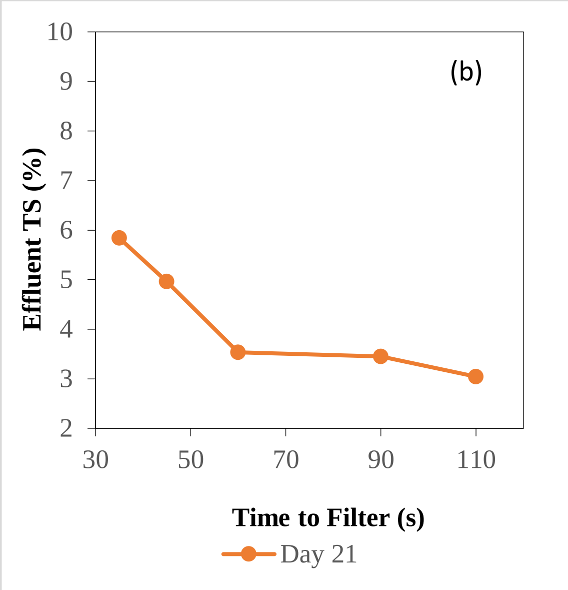


Figure 4.22 *The relationship between effluent TS and (a) Turbidity of filtrate and (b) TTF at flowrate 71 m^3h^{-1}*

Table 4.8 was produced by summarizing figures 4.20 to 4.22. According to the table 4.8, TTF was varied significantly up to 100 % while turbidity of filtrate varied around 46% at effluent TS at 5%. Certain range of dewaterability variation could be anticipated according to the influent sludge load, however dewaterability was varied beyond the influent sludge load. Hence, dewaterability of flocculated sludge not only depended on the influent sludge load but also physical operation within rotary drum thickener. Time to filter was more challengeable to monitor on real- time. Therefore, Time to filter was not a perfect parameter to determine optimum flocculent dosage on real- time or as a laboratory experiment. On the other hand, turbidity of filtrate can be recognized as a real-time controlling feedback parameter to manipulate flocculent dosage.

The turbidity of filtrate was varied 33%, 46% and 9% at influent flowrate 50 m^3h^{-1}, 65m^3h^{-1}, and 71 m^3h^{-1} respectively. Due to that, it was possible to use a single set point of turbidity of filtrate at particuler influent flowrate to manupilate flocculent dosage. The mean turbidity of filtrate values were calculated as 150 NTU, 80 NTU, and 60 NTU at flowrates 50 m^3h^{-1}, 65m^3h^{-1}, and 71 m^3h^{-1} respectively. However, the calculated mean turbidity of filtrate reached the minimum of turbidity of filtrate range at day12. Therefore, using single set point of turbidity of filtrate was less reliable to obtain the effluent TS% of 5$\pm$1 %.

The mean turbidity of the filtrate decreased from 150 NTU to 60 NTU when the influent flowrate increased. This was due to the lower HRT of thickener at higher flowrate, which required lower TTF. Hence, higher flocculent dosage was used at high influent flowrate to reduce turbidity of the filtrate.

Table 4.8 *TTF and turbidity of filtrate of effluent TS 5% and 5±1% at flowrate 50 m^3h^{-1}, 65 m^3h^{-1}.and 71 m^3h^{-1}*

Flowrate (m^3h^{-1})	Day	TTF at 5% TS Effluent (s)	TTF Range at 5±1 % TS Effluent (s)	Filtrate Turbidity at 5% TS Effluent (NTU)	Filtrate Turbidity Range at 5±1 % TS Effluent (NTU)
50	12	160	160-270	170	150-230
	13	140	120-170	150	120-180
	14	80	70-90	150	130-180
	15	-	-	120	100-210
	16	-	-	180	130-220
65	14	60	40-70	80	70-150
	17	100	80-110	70	60-100
	18	110	90-130	95	70-120
	19	70	60-120	80	70-130
	20	70	60-80	65	55-90
71	16	-	-	60	50-110
	21	45	35-55	55	50-70
	22	-	-	60	50-70

4.3.2 Possible Feedforward Parameters to Change Set Point of Turbidity of Filtrate

Influent flowrate and characteristics of primary sludge (TS, TSS, turbidity) can be used as feedforward parameters to change setpoint of turbidity of filtrate in order to obtain 5% TS in the effluent.

4.3.2.1 Turbidity of Supernatant of the Primary Sludge

The figure 4.23,4.24 and 4.25 represent the turbidity of filtrate with turbidity of supernatant, the turbidity of filtrate with influent TSS and the turbidity of filtrate with influent TS respectively at flowrates 50 $m^3 h^{-1}$, 65$m^3 h^{-1}$, and 71 $m^3 h^{-1}$.

Turbidity of supernatant was varied in a significant range in figure 4.30. Hence the operating equations relating turbidity of filtrate with turbidity of supernatant shown in figure 4.20 can be used to calculate the set point of the turbidity of filtrate. The operating equation for the flowrate of 50 $m^3 h^{-1}$ (figure 4.20a) had a better correlation between turbidity of filtrate and turbidity of supernatant when compared to the operating equations for the flowrates 65 $m^3 h^{-1}$ and 71 $m^3 h^1$. At influent flowrate 65 $m^3 h^{-1}$, the realibility of operation equation shown in figure 4.23b was not significantly improved to obtain effluent 5% TS. In the figure 4.23c, eventhough the turbidity of supernatant changed in a wide range, the turbidity of filtrate remained nearly constant. It was suggested turbidity of supernatant was not a good parameter to determine the set point for the turbidity of filtrate. Due to this disputive situation, use of turbidity of supernatant as the feed foward variable was doubtful.

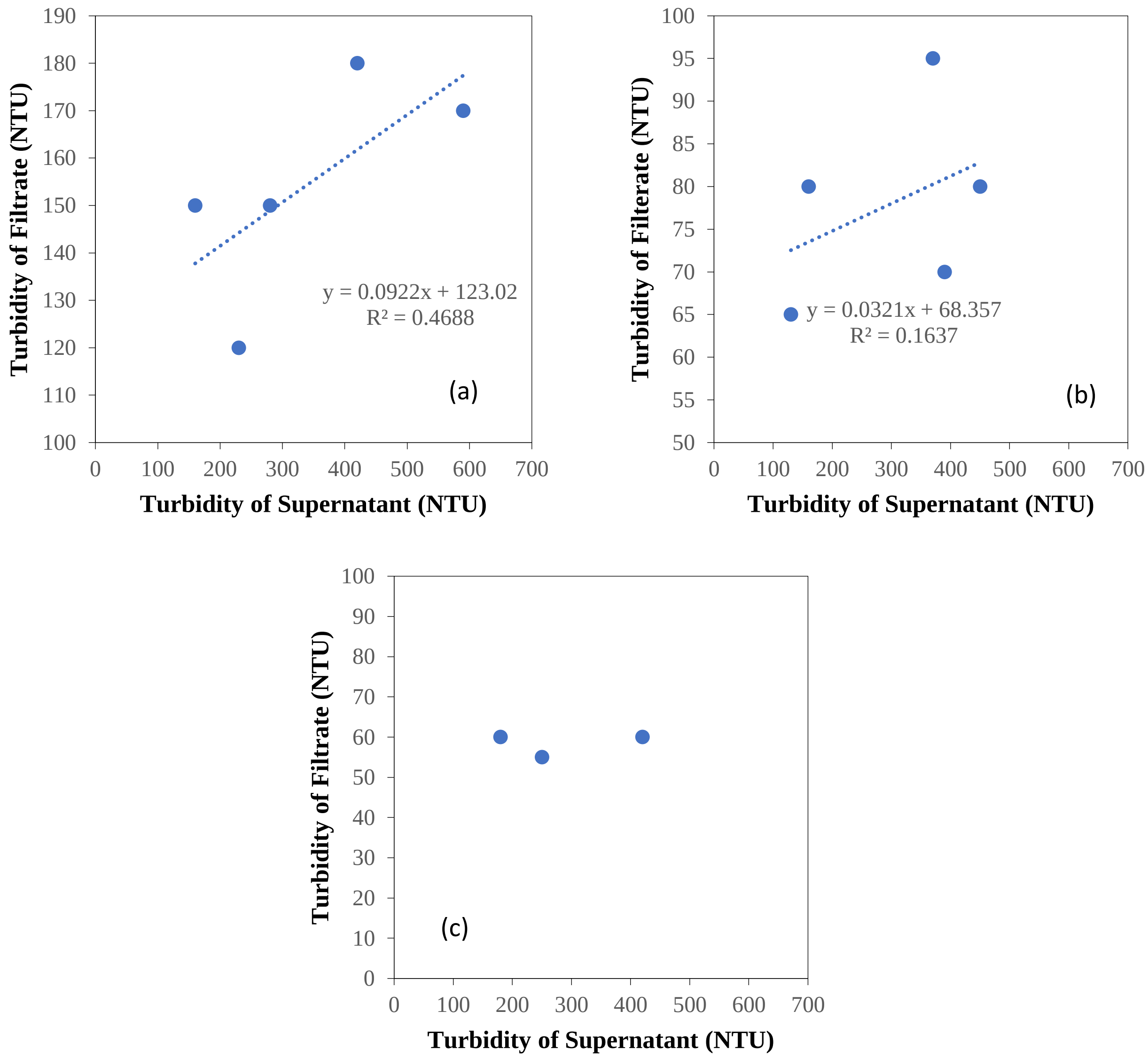


Figure 4.23 *The relationship between turbidity of supernatant and turbidity of filtrate at influent flowrate (a) 50* m^3h^{-1}*, (b)65* m^3h^{-1}*, (c)71* m^3h^{-1}

4.3.2.2 TSS of the primary sludge

The operating equation relating turbidity of filtrate with influent TSS shown in figure 4.24 can be used to calculate the set point of the turbidity of filtrate. When considering figure 4.24a, the data points were varied between narrow range of influent TSS. Hence, the operating equation varied around a turbidity of filtrate value around 150 NTU which was the mean turbidity of filtrate to obtain 5% effluent TS for 50 m^3h^{-1}. Therefore, the reliability of obtaining effluent TS % of 5 $\pm$ 1 % was not significantly increased when using the operating equation at 50 m^3h^{-1}. In the figure 4.24b, the operating equation relating turbidity of supernatant and influent TSS was more reliable in obtaining an effluent TS% of 5%. In the figure 4.24c, the turbidity of supernatant and influent TSS both showed a lower variation. Therefore, the influent TSS can be considered as a good parameter to calculate the set point for the turbidity of filtrate in this case.

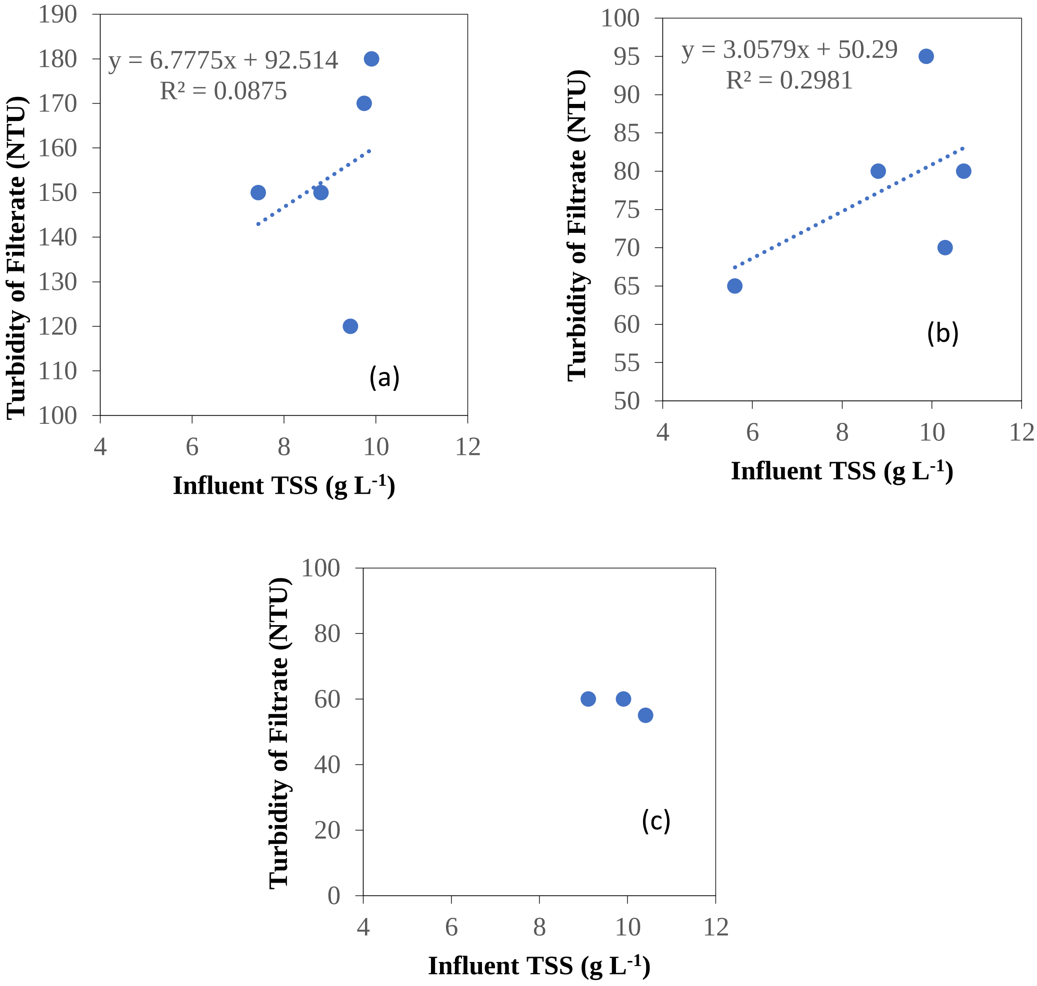


Figure 4.24 *The relationship between influent TSS and turbidity of filtrate at influent flowrate (a) 50 m^3h^{-1}, (b)65 m^3h^{-1}, (c)71 m^3h^{-1}*

4.3.2.3 TS of Primary Sludge

The operating equations relating turbidity of filtrate with influent TS shown in figure 4.25 can be used to calculate the set point of the turbidity of filtrate. Due to the consistent ratio between TSS and TS of primary sludge, figure 4.24 and figure 4.25 had similar variation. Hence, same explaination discirbed under figure 4.24 was valid for figure 4.25.

Therefore, the influent TS can be considered as a good parameter to calculate the set point for the turbidity of filtrate in this case.

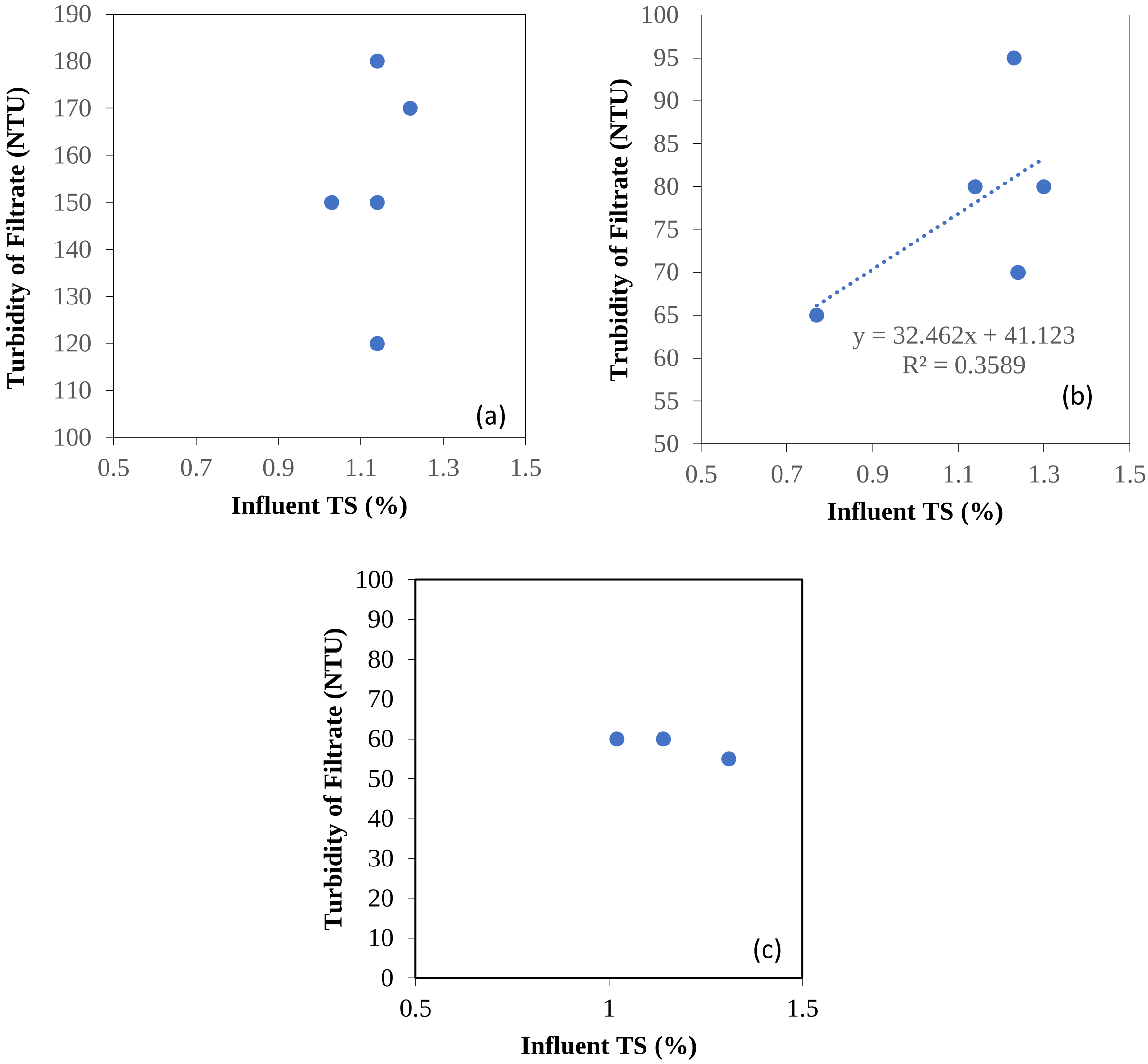


Figure 4.25 *The relationship between influent TS and turbidity of filtrate at influent flowrate (a) 50 m^3h^{-1}, (b)65 m^3h^{-1}, (c)71 m^3h^{-1}*

Overall, the influent wastewater characteristics had data points in a limited range. Hence, further experiments with more data points need to be conducted. However, the influent TS% and influent TSS can be recognized as better feed forward controlling variables to change setpoint of turbidity of filtrate in order to manipulate the thickening process.

4.3.3 Flowrate of Filtrate of Rotary Drum Thickener as a Feedback Controller

The absolute flowrate was not able to be measured due to the absence of a flowmeter at the thickener filtrate. Therefore, the flowrate of filtrate at each TS of 5% was calculated through material balance equation (Equation 2.2). The calculations of flowrate of filtrate with or without considering TS% at filtrate were included in Appendix 4.8**.** Table 4.9 illustrates the flowrate of filtrate at TS% of 5 % and range of flowrate at TS% within 5±1 %. Filtrate flowrate was varied within a considerable range when effluent TS% was 5±1 %. Therefore, flowrate corresponding to the effluent TS% of 5 % can be measured with sufficient accuracy.

Table 4.9 *Flowrate of filter at effluent TS 5% and 5±1% at influent flowrate 50 m^3h^{-1}, 65 m^3h^{-1}, and 71 m^3h^{-1}*

Flowrate (m^3 h^{-1})	**Day**	**Flowrate of Filtrate at 5% TS Effluent [a]**	**Flowrate of Filtrate at 5% TS Effluent [b]**	**Range of Flowrate of Filtrate at 5±1 % TS Effluent**
50	12	42.9	41.7	40.1-44.7
	13	44.7	43.6	42.5-46.2
	14	43.6	42.5	41.1-45.3
	15	43.6	42.5	41.2-45.3
	16	43.7	42.5	41.2-45.3
65	14	55.4	54.0	52.2-57.7
	17	54.0	52.7	50.3-56.6
	18	54.3	52.9	50.5-56.7
	19	53.2	52.0	49.3-55.9
	20	60.2	58.9	58.2-61.7
71	16	60.2	58.7	56.5-62.6
	21	57.6	56.3	53.2-60.6
	22	61.9	60.4	58.6-64.1

a –Flowrate was calculated by considering Filtrate TS
b- Flowrate was calculated without considering filtrate TS

According to the mass balance equation of thickener flowrate of filtrate at effluent TS 5% depended on influent sludge load and filtrate solid concentration. However, flowrate calculated without considering filtrate solid concentration was within the flowrate range which represented effluent TS 5±1 %. This was due to the low solid concentration in filtrate (TS%<0.15%).

Figure 4.26 shows filtrate flowrate variation with increasing effluent TS at influent flowrate 50 m^3 h^{-1}, 65 m^3 h^{-1}, and 71 m^3 h^{-1}. Filtrate of flowrate was calculated by assuming influent TS was 1 %, backwash flowrate was 3.86 m^3 h^{-1}, and filtrate TS was zero (Appendix 4.9). According the figure 4.26, the difference between flowrate of filtrates at two nearest effluent TS data points were more than 1 m^3 h^{-1} until effluent TS 6 %. Due to that, highly sensitive flowmeter would not be required for the filtrate of the thickener.

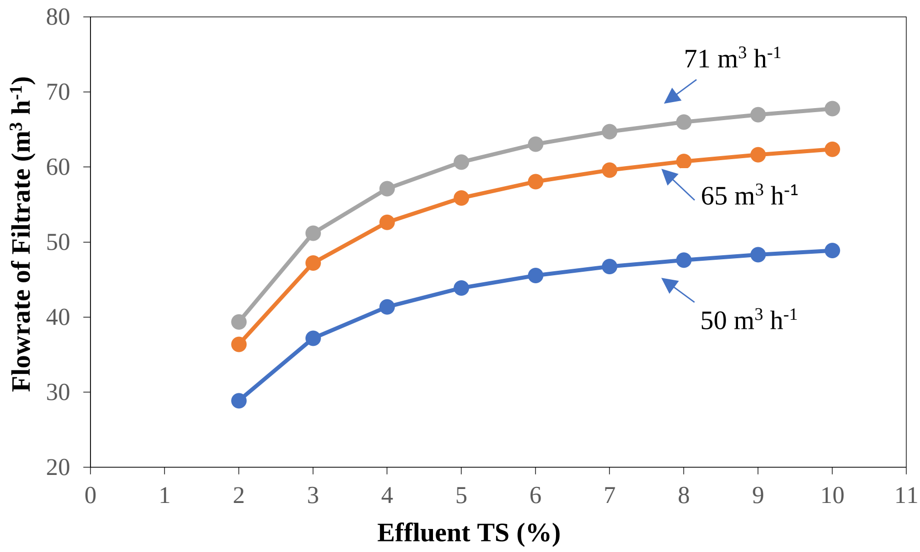


Figure 4.26 *Flowrate of filtrate at different effluent Ts at influent flowrate 50 m^3h^{-1}, 65 m^3h^{-1}, and 71 m^3h^{-1}*

Overall, flowrate of filtrate was a reliable feedback controlling variable to manipulate flocculent dosage. Then, a feed forward controller was required to recognize the set point of flowrate of filtrate.

The figures 4.27 represents the flowrate of filtrate calculated by considering filtrate TS with influent sludge load (kgTS h^{-1}) at flowrates 50 m^3 h^{-1} , 65 m^3 h^{-1}, and 71 m^3 h^{-1}. Inverse correlation between influent sludge load and flowrate of filtrate was shown in the figure. Filtrate sludge load was significantly lower than the influent sludge load. Therefore, effluent TS was mostly influenced by filtrate flowrate and influent sludge load according to the equation 2.2. Furthermore, an inverse relationship between filtrate flowrate and influent sludge load was obtained when achieving 5% TS from the effluent.

In conclusion, influent flowrate and TS% could be recognized as feed forward controlling parameters to change the set point of flowrate of filtrate. As a result, Flocculent dosage could be manipulated in order to obtain required flowrate.

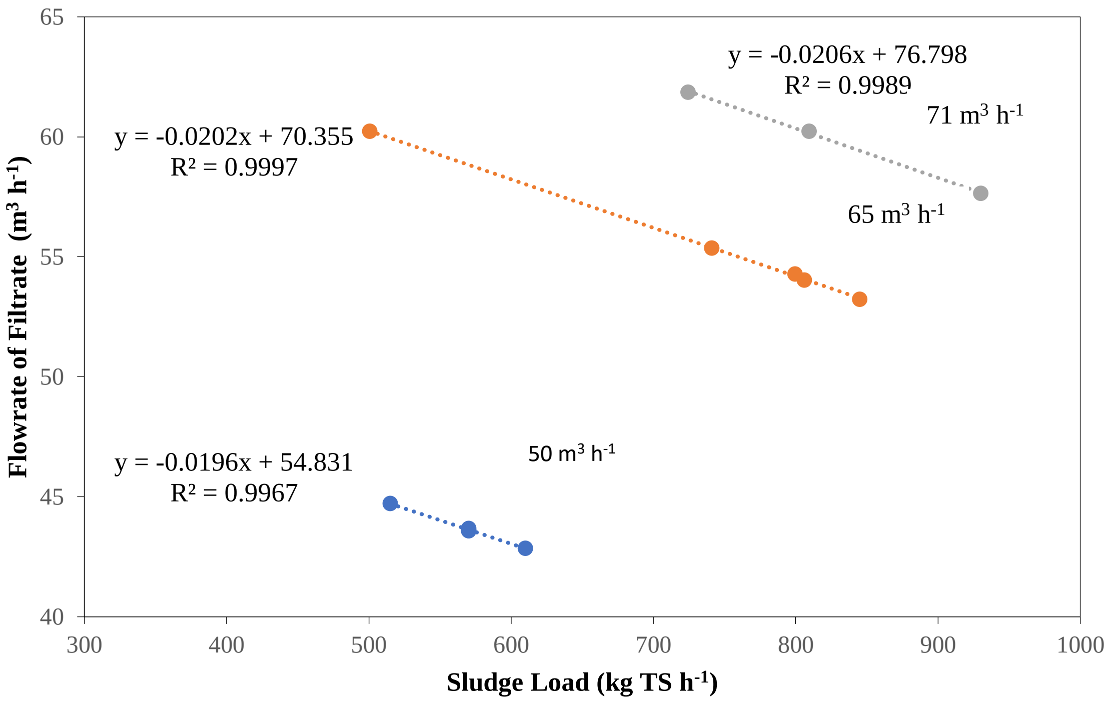


Figure 4.27 *The relationship between influent sludge load and flowrate of filtrate at influent flowrate 50 m^3h^{-1}, 65 m^3h^{-1}, and 71 m^3h^{-1}*

4.4 Control Loops for Primary Sludge Thickening Process

According to the results of full-scale experiments, backwash operation, flocculator mixer, and rotation speed of thickener can be optimized in order to obtain a stable thickening process. Optimized operational parameters (other than flocculent dosage) are presented in table 4.10. Flocculent dosage is the most influencing operational parameter for thickening process and must be varied to obtain the required solid concentration from the effluent. Five different controlling loops are identified and discussed below.

Table 4.10 *Optimized operational parameters of rotary drum thickener at SNJ WWTP*

Minimum Backwashing Time Period (seconds)	Maximum Time Between Two Backwash Cycles (minutes)	Rotational Speed of Thickener (rpm)	Flocculator Mixer
12	1	4.8	Turn on ; TS%<0.8% Turn off; TS%>1%

4.4.1 Controlling Loop 1

Figure 4.28 illustrates proposed controlling loop five for primary sludge thickening process. This method can be categorized as a feedback controlling method where TS % of effluent is measured as a feedback parameter to manipulate flocculent flowrate. Controlling loop 1 is the most reliable method to obtain effluent 5 % TS. However, sludge outlet of thickener is located directly over the sludge holdings tank and sludge does not move from thickener to tank continuously. Therefore, designing this control setup would be more challenging and finding an instrument to measure online TS 5% is doubtable.

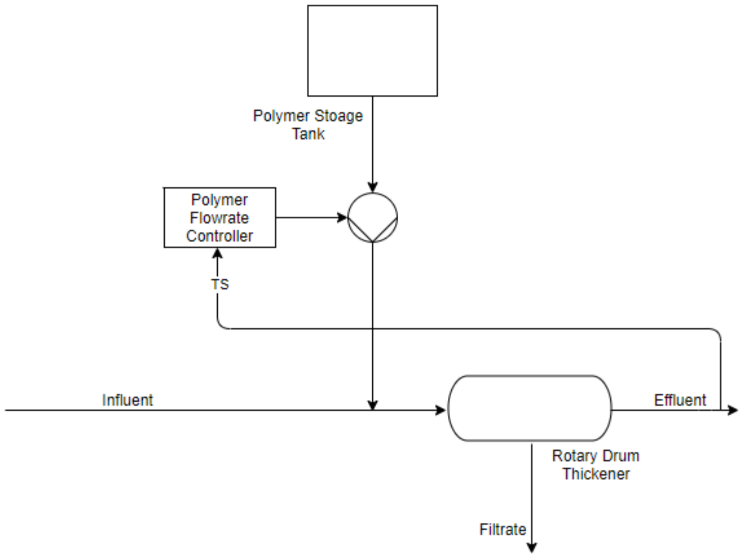


Figure 4.28 *Controlling loop one for primary sludge thickening process at SNJ WWTP*

4.4.2 Controlling Loop 2

Figure 4.29 illustrates proposed controlling loop two for primary sludge thickening process. This method can be categorized as feedforward controlling method where influent parameters such as TS, turbidity of supernatant, and flowrate (Q_{in}) are used to manipulate flocculent flowrate. Table 4.11 presents the selected flocculent dosage according to the influent parameters. Flocculent flowrate can be calculated through influent TS. Turbidity of supernatant can only be measured discontinuously because it required a time period for sedimentation. Therefore, design feasibility of such process is required other than installing turbidity meter before selecting this method. However, such designing requirement can be overcome if it is possible to find an industrial scale instrument which can measure influent turbidity. However, this method has the lowest reliability to obtain TS 5±1% on each day effluent due to this controlling method which considers only the influent parameters.

Table 4.11 *Required flocculent dosage for influent flowrate at 50 m^3h^{-1}, 65 m^3h^{-1}, and 71 m^3h^{-1}*

Flowrate ($m^3 h^{-1}$)	**Turbidity of Supernatant (NTU)**	**Flocculent Dosage (g Flocculent/ kg TS)**
50	>200	0.9-1
	<200	0.5
65	>200	1.2-1.3
	<200	0.8-0.9
71	>200	1.2-1.3
	<200	1.1

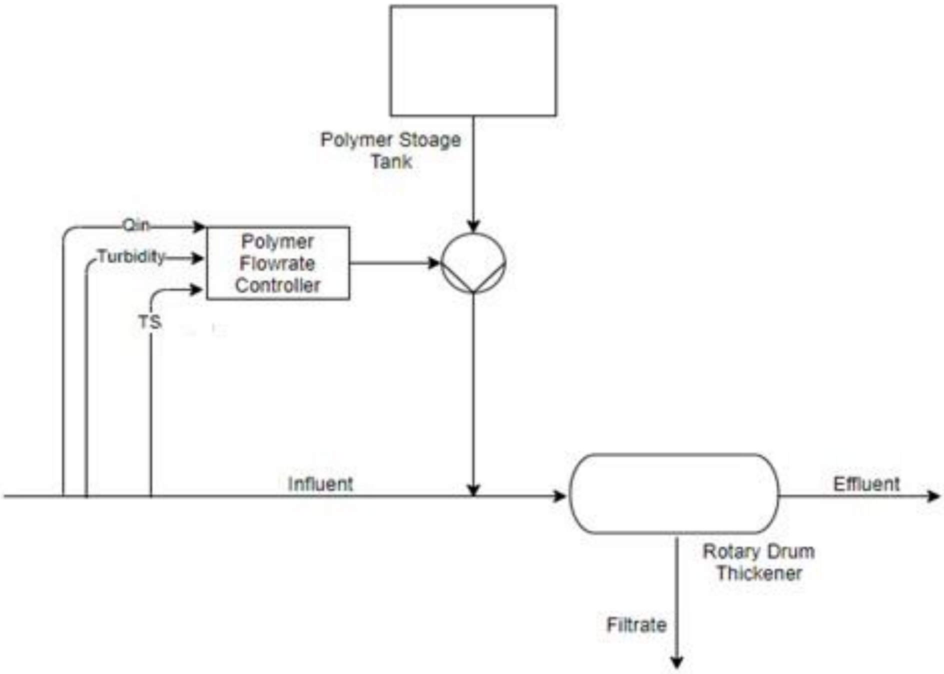


Figure 4.29 *Controlling loop two for primary sludge thickening process at SNJ WWTP*

4.4.3 Controlling Loop 3

Figure 4.30 illustrates proposed controlling loop three for primary sludge thickening process. This method can be categorized as feedforward and feedback controlling method where influent parameters such as TS and flowrate (Q_{in}) are considered as feedforward parameters while turbidity of filtrate is measured as feedback parameter to manipulate the flocculent flowrate. This method has higher reliability to obtain 5±1% TS compared to the controlling loop one. Feedforward parameters are used to determine turbidity set point of filtrate. Flocculent flowrate is changed according to the difference between actual and set point of filtrate turbidity. For example, flocculent flowrate is decreased when set point of turbidity of filtrate is lower than actual value. This method requires minimum process change to install inlet TS meter and turbidity meter for the filtrate.

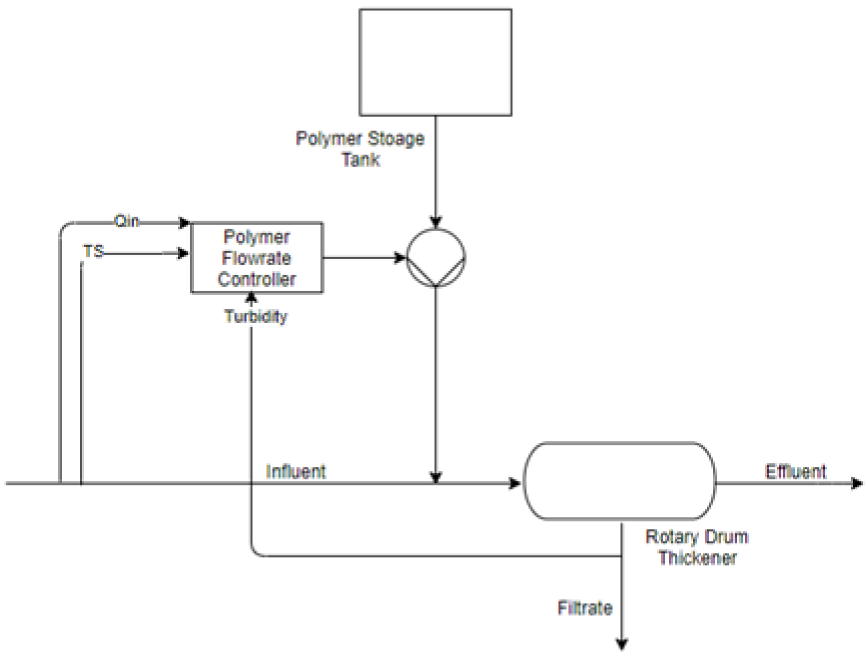


Figure 4.30 *Controlling loop three for primary sludge thickening process at SNJ WWTP*

4.4.4 Controlling Loop 4

Figure 4.31 illustrates proposed controlling loop four for primary sludge thickening process. This method can be categorized as feedforward and feedback controlling method where influent parameters such as TS and flowrate (Q_{in}) are considered as feedforward parameters while flowrate of filtrate is measured as feedback parameter to manipulate flocculent flowrate. Influent TS measuring meter and flowmeter to the filtrate are required for this method. Set point of flowrate of filtrate can be determined through two methods. Mass balance equation for thickener (equation 2.2) can be used to determine flowrate of filter by assuming filtrate TS to be zero.

However, error generated due to absence of filtrate TS can be reduced by using operation equations which are built by considering filter TS. Those operation equations to determine flowrate of filtrate were developed and discussed under section 4.3.3. Table 4.12 describes operating equations are shown in figure 4.27 for influent flowrate 50 $m^3 h^{-1}$, 65 $m^3 h^{-1}$, and 71 $m^3 h^{-1}$. This method has higher reliability to obtain 5±1% TS compared to the controlling loop one and two. This method is built without measuring absolute flowrate of filtrate. Although, according to the mass balance concept, this method can be considered as one of the most promising method to control thickener process.

Table 4.12 *Operation equations to determine flowrate of filtrate at influent flowrate 50 m^3h^{-1}, 65 m^3h^{-1}, and 71 m^3h^{-1}*

Influent Flowrate (m^3 h^{-1})	**Operation Equations to Determine Flowrate of Filtrate**
50	-0.0196 * influent sludge load+ 54.831
65	-0.0202* influent sludge load + 70.355
71	-0.0206 *influent sludge load + 76.798

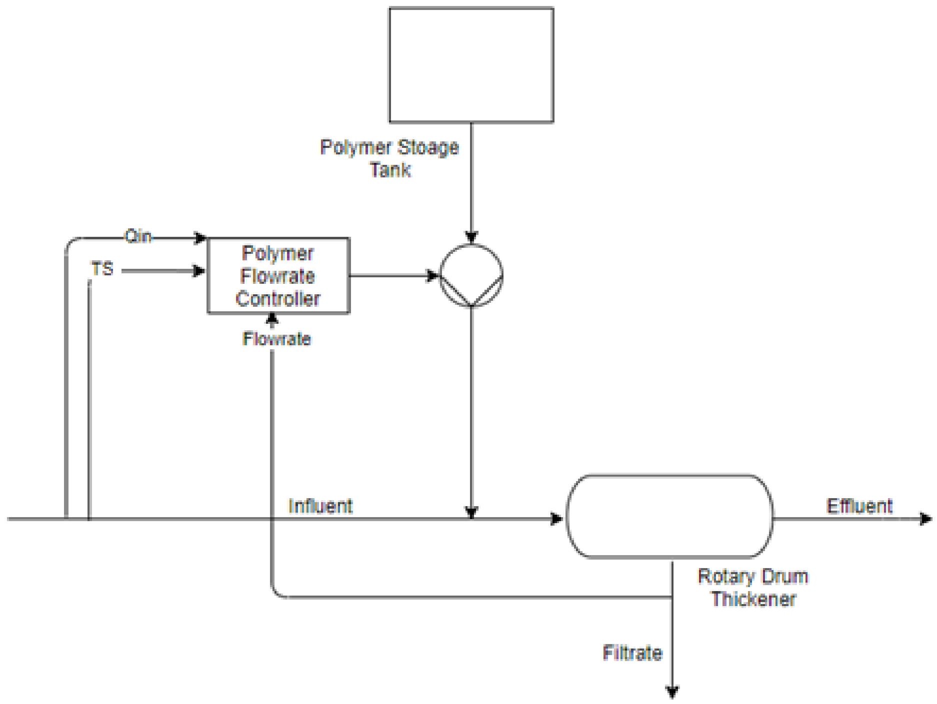


Figure 4.31 *Controlling loop four for primary sludge thickening process at SNJ WWTP*

4.4.5 Controlling Loop 5

Figure 4.32 illustrates proposed controlling loop five for primary sludge thickening process. This method can be categorized as feedforward and feedback controlling method where influent parameters such as TS and flowrate (Q_{in}) are considered as feedforward parameters while flowrate and TS of filtrate are measured as feedback parameters to manipulate flocculent flowrate. Mass balance equation (Equation 2.2) is used to calculate effluent TS. When the calculated effluent TS is lower than 5%, the flocculent flowrate is increased to reach effluent TS 5% and vice versa. This method has slightly higher reliability to obtain 5±1% TS compared to the above method. However, this method requires more instruments to control thickening process compared to the other controlling methods. Therefore, it is not economically viable option to control thickening process.

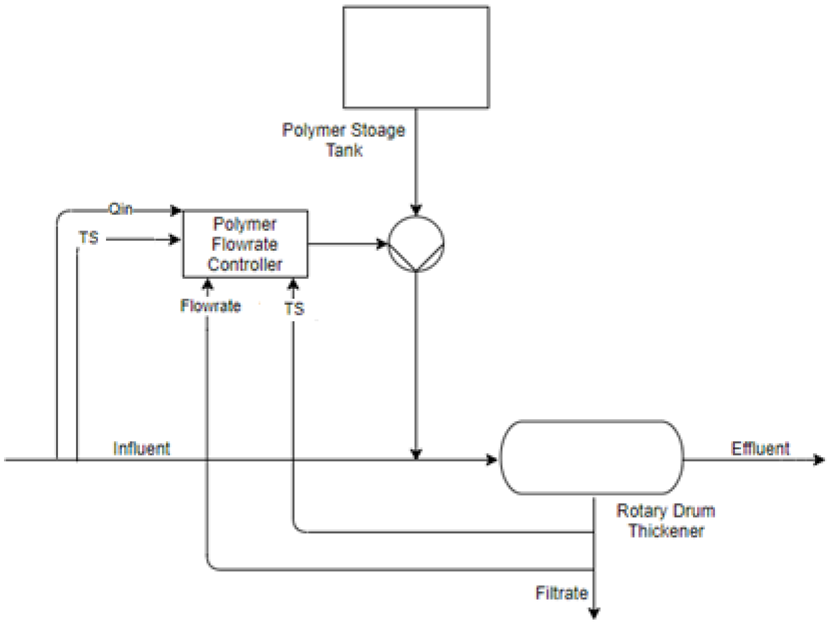


Figure 4.32 *Controlling loop five for primary sludge thickening process at SNJ WWTP*

Control loop three and four are considered as more favorable with respect to reliability to achieve effluent TS 5±1% and economical perspectives. Because such methods have more controlling ability of the thickening process and require less process change. However, detailed economic feasibility for each method should be carried out before selecting controlling method.

5. Error Analysis

This section reviews limitations and uncertainties associated with experimental procedure and results. Experiments have been conducted during January -March. Therefore, characteristics of primary sludge only represents the winter season, not the whole year. However, temperature of primary sludge is an influencing factor to the thickening process. In order to reduce uncertainty caused by seasonal variation, experiments should be conducted over a year.

5.1 Solid Analysis

TS of the primary sludge sample was measured according to the modified standard method (SM 2540 G). The modification was to use aluminum evaporating dishes instead of porcelain dishes. Aluminum has higher thermal conductivity compared to the porcelain (García et al., 2011). And Aluminum containers have higher surface area and lower thickness Therefore, aluminum containers require 5-10 minutes, while porcelain containers require 0.5-1 hours to reach room temperature. Hence, aluminum dishes have more advantages compared to the porcelain dishes.

Errors of this modification was estimated through 10 parallel primary sludge samples. Table 4.10 describes mean TS and standard deviation of P and A assay. TS of P assay was measured by standard procedure while modified standard method was used to measure TS of A assay. Errors produced due to modification was 5%. It was an acceptable error percentage. Hence, modified standard procedure was valid to measure TS in sludge sample. As well as lower standard deviation of TS of modified method (0.09) indicated lower random errors in this procedure.

Table 5.1 *Mean TS and standard errors of P and A assay*.

Assay ID	Mean TS± Standard Errors%
P	1.13±0.08
A	1.07±0.09
Mean deviation between assays %	5

5.1.1 Validation of Modified Standard Procedure (2540G)

Primary sludge samples were diluted with distilled water in 1:2 ratio and 1:4 ratio. Observed TS and expected TS of such dilutions are presented in Table 4.11 and 4.12. Expected TS was calculated by using mean TS of A assay. Average error percentage was less than 5%. Therefore, modified standard procedure (2540G) was a valid method for analyzing primary sludge samples.

Table 5.2 *Error percentage between observed and expected TS% in dilution ratio 1:2*

Sample ID	Observed TS%	Expected TS%	Error %
1-2D	0.35	0.36	1.52
2-2D	0.36	0.35	2.38
3-2D	0.33	0.35	6.13
Average error %			3.34

Table 5.3 *Error percentage between observed and expected TS% in dilution ratio 1:4*

Sample ID	Observed TS%	Expected TS%	Error %
1-4D	0.21	0.22	1.86
2-4D	0.22	0.22	1.01
3-4D	0.20	0.22	7.31
Average error %			3.39

A t-distribution analysis with 90% certainty was used to determine errors of the TS and TSS of primary sludge throughout this study. Coefficient of variation (CV) of TS and TSS of influent sludge replicates were 2.64% and 6.2% (Appendix 4.10). Hence, TS measurements were within acceptable range of error (5%) but error of TSS was slightly higher than 5%. This was possible due to the low volume (4-6 mL) of samples used to measure TSS. CV of effluent TS was also lower than 3% (Appendix 4.10).

5.2 Time to Filter Test

The experimental setup caused to produce uncertainty in this analysis. Filter paper was sealed with prewetting with distilled water but seal was broken in few occasions. Therefore, setup should be modified or more parallel tests should be conducted in order to eliminate this uncertainty.

6. Conclusions

Laboratory scale experiments confirmed that the dewaterability of primary sludge provided from microscreen changed each day even though constant flocculent dosage was used (g flocculent/ kg TS). Frequent fluctuation in sludge dewaterability provided much more challenging sludge thickening process for primary sludge from microscreen compared to the conventional sedimentation method. The microscreens and the absence of a buffer tank prior to the thickening process at SNJ WWTP caused to produce more inhomogeneous primary sludge. Hence, strict process controlling system is required for primary sludge thickening process at SNJ WWTP.

Average pH and temperature of primary sludge were 6.9 and 5 °C respectively and they were nearly constant throughout the study period. Therefore, such parameters of primary sludge did not influence the dewaterability variation during this research. Conductivity and alkalinity of primary sludge varied over the study period, but it did not provide enough evidence to build correlation with dewaterability variation of primary sludge according to the theories of bridging model. However, VFA concentration and turbidity of supernatant of primary sludge represented septicity and colloidal fraction respectively and were recognized as the most influencing characteristics to change dewaterability of the primary sludge. Septic sludge resulted in producing more colloidal solids. Hence, linear relationship was identified between septicity and turbidity of supernatant of primary sludge. Septic conditions required a higher flocculent dosage, most likely due to higher surface area of colloidal solids. The required flocculent dosage in order to obtain expected dewaterability should be determined with solids load and size fraction (particulate and colloidal solids) not only by solids load of the primary sludge.

Mixed sludge was more complicated in obtaining consistent dewaterability compared to the dewatering of biological sludge and primary sludge separately. Dewaterability of mixed sludge significantly changed when primary to biological sludge ratio changed. As well as, primary sludge fraction was equal or higher than biological fraction in mixed sludge samples and optimum flocculent dosage for primary sludge had higher deviation compared to the biological sludge. Hence, a fixed dewaterability was not possible to obtain from the mixed sludge through constant flocculent dosage.

The experiments with flocculator mixer suggested turbulence produced by mixer causing breaking of flocs and as a result, it lowered the dewaterability compared to the experiments without mixer usage when influent TS% was greater than 1%. However, turbulence produced by mixer was required to obtain higher dewaterability compared to the one without mixer usage when influent TS was lower than 0.8%. Hence, flocculator mixer could be optimized by considering influent TS to achieve higher dewaterability. As a result, flocculent requirement of thickening process would be reduced.

Rotational speed of drum thickener resulted in changing effluent solid concentration. Expected effluent concentration (5±1 of TS%) could not be obtained only varying the rotational speed of the drum thickener. Highest effluent solid concertation was more likely to reach when rotational speed was 4.8 rpm. Therefore, optimum rotational speed was considered as 4.8 rpm due to lower flocculent requirement in order to obtain expected solid concentration. At optimum rotational speed, minimum of 12 seconds required to clean the whole filter of the drum thickener. Effluent solids concentration was significantly reduced when time gap between two backwash cycles was greater than 1 minute. Due to that, optimum backwash mechanism could be considered as minimum of 12 seconds of backwashing and maximum 1 minute between 2 backwash cycles. Optimizing the backwash cycle will reduce usage of process water.

Flocculent dosage was identified as a main manipulated variable to obtain expected effluent solids concentration. Effluent solids concentration had better correlation with g flocculent/ kg TS compare to the g flocculent/kg TSS. Required flocculent dosage to obtain effluent TS 5% was reduced when increasing influent flowrate from 50 m^3 h^{-1} to 71 m^3 h^{-1}. As well as required flocculent dosage to obtain, effluent TS 5% was reduced when turbidity of supernatant of primary sludge was lower than 200 NTU and vice versa. Turbidity of filtrate and time to filter of flocculated sludge were varied over measurable range when flocculent dosage changed. However, turbidity of filtrate was a better controlling parameter compared to the time to filter parameter.

TS, TSS, inlet flowrate, and turbidity of supernatant were identified as feedforward parameters while turbidity of filtrate, flowrate of filtrate and effluent TS were identified as feedback parameters to manipulate flocculent flowrate of the primary sludge thickening process. Five different controlling loops were developed by considering all these feedback and feedforward parameters. Controlling loop two and three were recognized as the best options to control the thickening process due to the requirement of lower process change and had acceptable levels of reliability to obtain effluent TS % of 5% compared to the other controlling methods.

The methodology succeeded to achieve the objectives of this study and uncertainty of solid analysis was low (<5%). However, recommendations to improve methodology was included in “Recommendations” section.

7. Recommendations

This study was conducted over a short time period and concluded that flocculent dosage was a crucial parameter for thickening process. Flowmeter should be installed to the filtrate of the thickener. After that, effects of flocculent dosage to thickening process should be investigated at least over a year. Furthermore, experiments over a year will be facilitated to investigate effect of seasonal variation of primary sludge for the thickening process. Detailed economical and design feasibility should be carried out before selecting most suitable controlling method from proposed controlling methods for thickening process.

Performance of rotary drum filter impacted the sludge thickening process. Hence further optimizing of rotary drum filter would result in lowering the deviation of influent sludge characteristics of the thickening process. According to the current method, sludge load to the thickener is varied significantly with influent sludge load to the treatment process due to fixed backwashing time period. A suggestion is to optimize rotary drum filter to change rotational speed and backwashing period with respect to influent sludge load to the treatment plant. Several studies can be conducted to get a deep knowledge on thickening process. They are;

- Develop CFD models for flocculator mixer and rotary drum thickener in order to investigate particle movement throughout the thickening process.
- Determine particle size distribution (Particulate and colloidal) of primary sludge and biological sludge. As well as its impact to the dewaterability and thickening process.
- Another interesting area is to determine floc geometry (fractal numbers D_1, D_2, D_B) of primary, biological and mixed sludge. It would be helpful in further understanding about dewaterability of the particular sludge.

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Appendix

Appendix 1.1 - Calculation of SRT of Anerobic Digester at SNJ WWTP

Average primary sludge production by drum filters = 10 tons per day
Assume inlet TS was 1% , inlet sludge load to the thickener = 1000 tons per day

Table 9.1 *Primary sludge production load at different effluent TS*

TS % after thickening primary sludge	Production per day (tons)
2	500
3	333
4	250
5	200
6	167
7	143

Total value of secondary sludge and external sludge to the digesters per day= 240 tons
Digester volume = 7000 m^3
SRT was calculated by following below equation, Assume 1 tons sludge = 1 m^3 of sludge

$$\text{SRT} = \frac{\text{Digester volume } (m^3)}{\text{Total sludge per day} (\ m^3 d^{-1})}$$

Appendix 3.1- Flocculent dosage calculating equation for mixed sludge

Optimum flocculent dosage for primary sludge = D_p
Optimum flocculent dosage for secondary sludge = D_S
Primary sludge volume in mixed sludge = V_p
Secondary sludge volume in mixed sludge =V_s

$$Mixed\ sludeg\ flocculent\ dosage = \frac{D_p * V_p + D_s * V_s}{200\ mL}$$

Appendix 4.1- Calculation of TSS/TS ratio

Table 9.2 *Primary sludge TS to TSS ratio*

Day	TS %	TSS ($g\ L^{-1}$)	TSS/TS
1	0.92	6.71	0.73
2	1.07	7.73	0.72
3	0.62	4.71	0.76
4	0.81	6.06	0.75
5	1.44	11.7	0.81
6	1.34	10.87	0.81
7	1.38	11.25	0.81
8	1.02	8.03	0.78
Mean TS/TSS ±Standard errors			0.77±0.04

Appendix 4.2- Laboratory scale experiments- Primary sludge

Assume flocculent density as 1 g mL^{-1}

Table 9.3 *Raw data of day 1 at lab scale experiments*

Flocculent volume(ml)	Flocculent weight(g)	g Flocculent/ kg TS	TTF(s)	Filtrate Turbidity (NTU)
2	0.0018	0.98	300	320
3	0.0027	1.47	67	261
4	0.0036	1.96	34	153
5	0.0045	2.45	23	26
6	0.0054	2.93	22	22
7	0.0063	3.42	20	21

Table 9.4 *Raw data of day 2 at lab scale experiments*

Flocculent volume(ml)	Flocculent weight(g)	g Flocculent/ kg TS	TTF(s)	Filtrate Turbidity (NTU)
1	0.0009	0.42	>300	664
2	0.0018	0.84	180	350
2.5	0.0023	1.05	90	297
3	0.0027	1.26	60	237
3.5	0.0032	1.47	42	206
4	0.0036	1.68	30	170

Table 9.5 *Raw data of day 3 at lab scale experiments*

Flocculent volume(ml)	Flocculent weight(g)	g Flocculent/ kg TS	TTF(s)	Filtrate Turbidity (NTU)
1	0.0009	0.73	53	261
2	0.0018	1.45	23	127
2.5	0.0023	1.81	21	68
3	0.0027	2.18	112	25
3.5	0.0032	2.54	<300	21
4	0.0036	2.90	<300	24

Table 9.6 *Raw data of day 4 at lab scale experiments*

Flocculent volume(ml)	Flocculent weight(g)	g Flocculent/ kg TS	TTF(s)	Filtrate Turbidity (NTU)
1	0.0009	0.56	<300	340
2	0.0018	1.11	120	250
2.5	0.0023	1.39	53	206
3	0.0027	1.67	32	136
3.5	0.0032	1.94	30	101
4	0.0036	2.22	23	68

Table 9.7 *Raw data of day 5 at lab scale experiments*

Flocculent volume(ml)	Flocculent weight(g)	g Flocculent/ kg TS	TTF(s)	Filtrate Turbidity (NTU)

3	0.0027	0.94	120	407
3.5	0.0032	1.09	90	275
4	0.0036	1.25	47	250
5	0.0045	1.56	31	136
6	0.0054	1.88	20	46
7	0.0063	2.19	24	33

Table 9.8 *Raw data of day 6 at lab scale experiments*

Flocculent volume(ml)	Flocculent weight(g)	g Flocculent/ kg TS	TTF(s)	Filtrate Turbidity (NTU)
4	0.0036	1.34	<300	433
5	0.0045	1.68	240	304
6	0.0054	2.01	90	260
7	0.0063	2.35	43	139
8	0.0072	2.69	34	18
9	0.0081	3.02	29	5

Table 9.9 *Raw data of day 7 at lab scale experiments*

Flocculent volume(ml)	Flocculent weight(g)	g Flocculent/ kg TS	TTF(s)	Filtrate Turbidity (NTU)
4	0.0036	1.30	150	353
5	0.0045	1.63	45	223
6	0.0054	1.96	40	206
7	0.0063	2.28	30	90
8	0.0072	2.61	90	20
9	0.0081	2.93	150	22

Table 9.10 *Raw data of day 8 at lab scale experiments*

Flocculent volume(ml)	Flocculent weight(g)	g Flocculent/ kg TS	TTF(s)	Filtrate Turbidity (NTU)
2	0.0018	0.88	150	350
3	0.0027	1.32	71	200
4	0.0036	1.76	42	138
5	0.0045	2.21	25	60
6	0.0054	2.65	165	45
7	0.0063	3.09	240	10

Appendix 4.3- Laboratory scale experiments- Mixed sludge

Table 9.11 *Raw data of day 9 at lab scale experiments mixed sludge*

Secondary ml	Primary ml	Secondary: Primary	Flocculent volume (ml)	Polymer weight(g)	TS weight in 200 ml sample(kg)	g polymer/kg TS	TTF (s)
20	180	01:09	4.2	0.0038	0.0018	2.1544	25
40	160	02:08	5.4	0.0049	0.0020	2.4097	23
60	140	03:07	6.6	0.0059	0.0023	2.6062	26
80	120	04:06	7.8	0.0070	0.0025	2.7622	30
100	100	05:05	9	0.0081	0.0028	2.8890	30

Table 9.12 *Raw data of day 10 at lab scale experiments mixed sludge*

Secondary ml	Primary ml	Secondary: Primary	Flocculent volume (ml)	Polymer weight(g)	TS weight in 200 ml sample(kg)	g polymer/kg TS	TTF (s)
20	180	01:09	7	0.0063	0.0024	2.66	40
40	160	02:08	8	0.0072	0.0026	2.80	45
60	140	03:07	9	0.0081	0.0028	2.92	70
80	120	04:06	10	0.009	0.003	3.02	55
100	100	05:05	11	0.0099	0.0031	3.11	90

Table 9.13 *Raw data of day 11 at lab scale experiments mixed sludge*

Secondary ml	Primary ml	Secondary: Primary	Flocculent volume (ml)	Polymer weight(g)	TS weight in 200 ml sample(kg)	g polymer/kg TS	TTF (s)
20	180	01:09	4.2	0.0038	0.0018	2.1544	25
40	160	02:08	5.4	0.0049	0.0020	2.4097	23
60	140	03:07	6.6	0.0059	0.0023	2.6062	26
80	120	04:06	7.8	0.0070	0.0025	2.7622	30
100	100	05:05	9	0.0081	0.0028	2.8890	30

Appendix 4.4 – Calculation of G and retention time

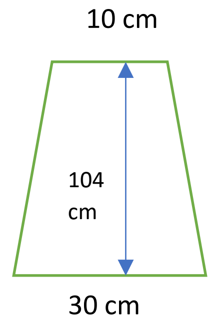

Figure 9.1 *Schematic diagram of paddles*

Area of paddles(A) = 0.208 m^2

Relative velocity of paddles (v_p) = 0.75*tip velocity of paddles (v)

$$\text{Tip velocity} = \frac{2\pi * N}{60} * r$$

Radius of paddle (r) = 0.15 m

Rotational speed of paddle = 50 rpm

$$\text{Tip velocity} = 0.78 \text{ m s}^{-1}$$

Relative velocity of paddles (v_p) =0.59 m s^{-1}

$$\text{Power of paddles (P)} = \frac{C_D * A * \rho * v_p^3}{2}$$

Assume coefficient of drag of paddles (C_D)= 1.8

Assume density of primary sludge (ρ) 0 1000 kg m^{-3}

$$P= 38.44 \text{ W}$$

$$\text{Velocity gradient of paddles } G= \sqrt{\frac{P}{\mu * V}}$$

Volume of reactor= 0.52 m^3 ; Dynamic viscosity (μ)= 1.139 *10^{-3} Ns m^{-2}

$$G = 254.75 \text{ s}^{-1}$$

$$\text{Retention time at 65 m}^3\text{ h}^{-1} = \frac{V}{Q} = \frac{0.52}{65} = 0.48 \text{ minutes}$$

Appendix 4.5 – Full scale experiments- flocculent dosage

- **Influent flowrate of 50 m^3 h^{-1}**

Table 9.14 *Raw data of day 12 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
690	150	6.07	140	1.02	1.27
628	170	4.77	160	0.93	1.15
560	220	4.25	240	0.83	1.03
502	250	3.45	<300	0.74	0.92
460	270	3.30	<300	0.68	0.84

Table 9.15 *Raw data of day 13 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
732	60	9.11	60	1.28	1.78
586	120	5.84	120	1.02	1.43
523	160	4.53	155	0.91	1.27
481	180	3.88	180	0.84	1.17
439	210	3.09	210	0.77	1.07

Table 9.16 *Raw data of day 14 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
418	80	9.30	50	0.66	0.86
356	110	7.02	70	0.56	0.73
314	160	4.60	80	0.50	0.64

Table 9.17 *Raw data of day 15 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
711	60	7.96	-	1.12	1.35
607	130	4.73	-	0.96	1.15
523	190	4.20	-	0.83	0.99

Table 9.18 *Raw data of day 12 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
753	90	7.33	-	1.19	1.37
649	130	6.16	-	1.02	1.18
523	230	3.80	-	0.83	0.95

- **Influent flowrate of 65 m^3 h^{-1}**

Table 9.19 *Raw data of day 14 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
753	60	6.37	50	0.91	1.18
711	60	6.53	44	0.86	1.12
670	100	4.18	60	0.81	1.05
628	85	4.86	55	0.76	0.99
523	150	3.99	70	0.64	0.82

Table 9.20 *Raw data of day 17 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
1256	65	5.8	90	1.40	1.69
1130	75	4.37	104	1.26	1.52
795	200	2.82	<300	0.89	1.07
585	260	2.53	<300	0.65	0.79

Table 9.21 *Raw data of day 18 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
1402	55	7.41	70	1.58	1.96
1256	65	6.26	90	1.41	1.76
1172	90	5.25	110	1.32	1.64
1067	115	4.18	120	1.20	1.49
900	160	3.35	180	1.01	1.26

Table 9.22 *Raw data of day 19 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
1423	50	7.7	50	1.52	1.84
1256	80	4.96	60	1.34	1.63
1151	130	3.99	120	1.23	1.49
924	180	3.62	180	0.98	1.20
732	320	3.34	<300	0.78	0.95

Table 9.23 *Raw data of day 20 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
607	30	9.09637487	40	1.09	1.47
544	40	9.22038252	45	0.98	1.32
502	60	5.29483023	60	0.90	1.22
418	110	2.86107097	90	0.75	1.02

- **Influent flowrate of 71 m^3 h^{-1}**

Table 9.24 *Raw data of day 16 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
1256	35	8.57	-	1.40	1.61
1109	60	4.62	-	1.23	1.42
774	165	3.21	-	0.86	0.99

Table 9.25 *Raw data of day 21 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
1465	50	5.84	35	1.34	1.72
1386	55	4.96	45	1.27	1.63
1214	80	3.53	60	1.11	1.43
1107	100	3.45	90	1.01	1.30
900	150	3.04	110	0.82	1.06

Table 9.26 *Raw data of day 22 at full scale experiments with different flocculent dosage*

Polymer dosage (L hr^{-1})	Filtrate turbidity (NTU)	TS%-Effluent	TTF (s)	g polymer/ kg TS	g polymer/ kg TSS
1047	40	8.68	-	1.30	1.46
921	55	5.25	-	1.14	1.28
816	70	3.82	-	1.01	1.14

Appendix 4.6 -HRT values of drum thickener

Length of thickener(L)= 4.72 m

Radius of thickener (r)= 0.45 m

Depth of sludge (d)= 0.15 cm

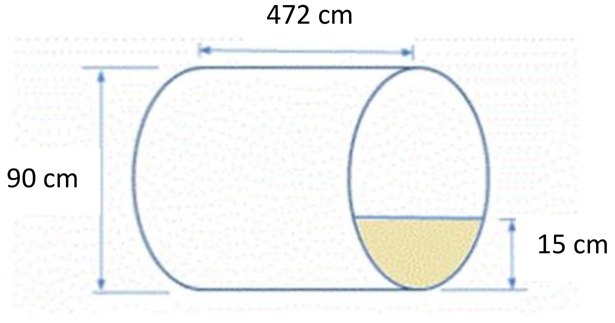

Figure 9.2 *Dimensions of drum thickener*

$$\text{Volume of drum thickener (V)} = L * \{\cos^{-1}\left(\frac{r-h}{r}\right) * r^2 - (r-h) * \sqrt{2hr - h^2}\}$$

$$V=0.0329\ m^3$$

Assume influent sludge concentration as 1% TS,

$$\text{Sludge flowrate inside thickener (Q)}= \frac{effluent\ sludge\ flowrate\ (kg\ TS\ h^{-1})}{influent\ sludge\ load\ (kg\ TS\ m^{-3})}$$

At effluent sludge load 5% of TS and influent flowrate at 50 $m^3\ h^{-1}$

$$Q_{50}= \frac{500\ kg\ TS\ h^{-1}}{50\ kg\ TS\ m^{-3}} = 10\ m^3h^{-1}$$

At effluent sludge load 5% of TS and influent flowrate at 65 $m^3\ h^{-1}$

$$Q_{65}= \frac{650\ kg\ TS\ h^{-1}}{50\ kg\ TS\ m^{-3}} = 13\ m^3h^{-1}$$

At effluent sludge load 5% of TS and influent flowrate at 71 $m^3\ h^{-1}$

$$Q_{71}= \frac{710\ kg\ TS\ h^{-1}}{50\ kg\ TS\ m^{-3}} = 14.2\ m^3h^{-1}$$

HRT of thickener at influent flowrate at 50 $m^3\ h^{-1}$

$$HRT=\frac{V}{Q} = \frac{0.329\ m^3}{10\ m^3h^{-1}} = 2\ minuts$$

HRT of thickener at influent flowrate at 65 $m^3\ h^{-1}$

$$HRT=\frac{V}{Q} = \frac{0.329\ m^3}{13\ m^3h^{-1}}= 1.5\ \text{minutes}$$

HRT of thickener at influent flowrate at 71 $m^3\ h^{-1}$

$$HRT=\frac{V}{Q} = \frac{0.329\ m^3}{14.2\ m^3h^{-1}}=1.4\ \text{minutes}$$

Appendix 4.7 - Effect of flocculent dosage on time to filter of flocculent sludge and filtrate turbidity.

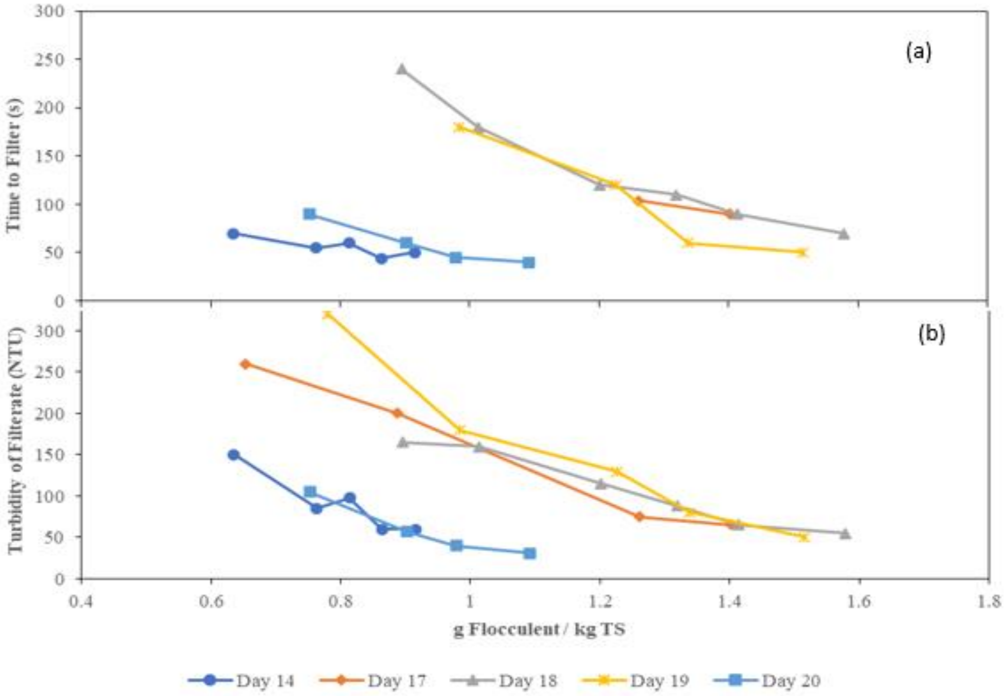

Figure 9.3 *Effect of flocculent dosage on ;(a) TTF, (b) Turbidity of filtrate at 65 m* $^{3}h^{-1}$

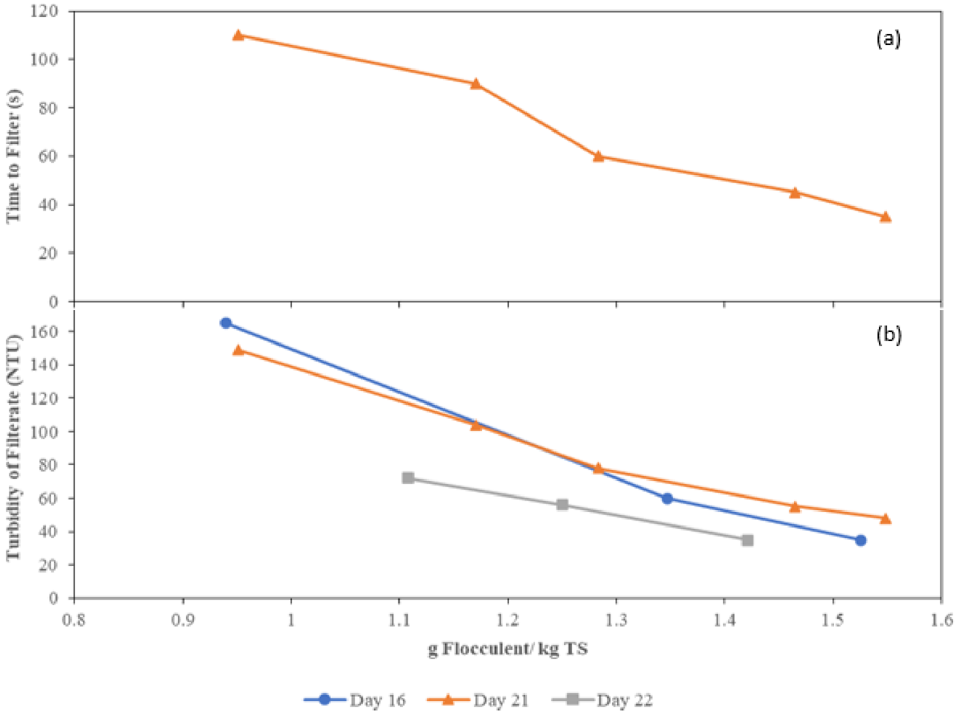

Figure 9.4 *Effect of flocculent dosage on ;(a) TTF, (b) Turbidity of filtrate at 71 m* $^{3}h^{-1}$

Appendix 4.9 – Flowrate of filtrate at effluent TS 5%

Equation 2.2 was rearranged at effluent TS at 5% to calculate flowrate of filtrate.

$$Q_r = \frac{Q_i(TS_i - 5) - 5 * Q_b}{(TS_r - 5)} \text{-------------(Equation 2.3)}$$

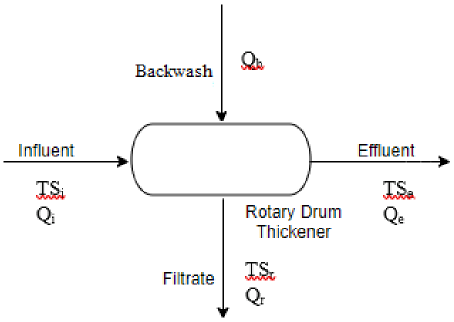

***Figure 9.5** Notations of mass and flowrate of each stream in rotary drum thickener*

Assume dissolved solids of filtrate was 40% of the difference between influent TS and TSS. Hence, Average dissolve solids % =0.4*(1-0.77) =0.1 %

Figure 9.6 was used to calculate TSS% of the filtrate. This figure was produced by measuring TSS and turbidity over several hours. Raw data of this figure was induced in "Raw data" document.

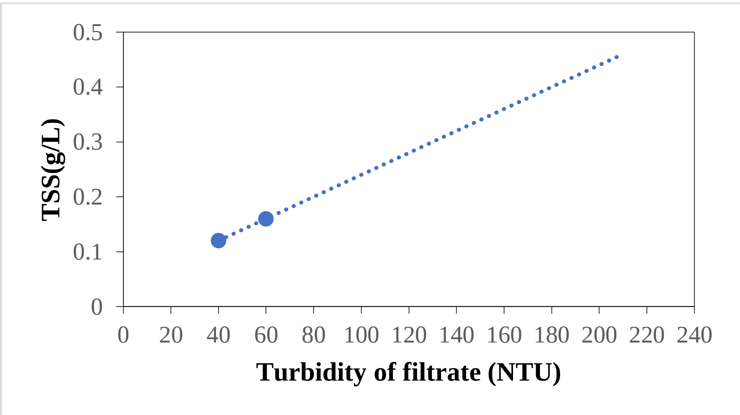

***Figure 9.6** The relationship between filtrate turbidity and TSS*

At flowrate 50 m^3h^{-1}, Equation 2.3 was used to calculate filtrate flowrate

Day	Q_i (m^3h^{-1})	TS_i %	Q_b (m^3h^{-1})	TS_r %	Q_r (m^3h^{-1})
12	50	1.22	3.86	0.17	42.9

Similarly, all the flowrate of filtrate respective to the each day was calculated.

Appendix 4.9 – Flowrate of filtrate at different effluent TS

Equation 2.2 was rearranged to calculate flowrate of filtrate. And assume filtrate TS was zero and influent TS was 1%.

$$Q_r = Q_i + Q_b - \left(\frac{Q_i * TS_i}{TS_e}\right)$$

Table 9.6 *Flowrate of filtrate under different effluent TS at influent flowrate 50 m^3h^{-1}, 65 m^3h^{-1}, 71m^3h^{-1}*

TS%	Q_r at 50 m^3h^{-1}	Flowrate Difference between nearest two TS points	Q_r at 65 m^3h^{-1}	Flowrate Difference between nearest two TS points	Q_r at 71 m^3h^{-1}	Flowrate Difference between nearest two TS points
2	28.86	8.33	36.36	10.83	39.36	11.83
3	37.19	4.17	47.19	5.42	51.19	5.92
4	41.36	2.50	52.61	3.25	57.11	3.55
5	43.86	1.67	55.86	2.17	60.66	2.37
6	45.53	1.19	58.03	1.55	63.03	1.69
7	46.72	0.89	59.57	1.16	64.72	1.27
8	47.61	0.69	60.74	0.90	65.99	0.99
9	48.30	0.56	61.64	0.72	66.97	0.79
10	48.86	-	62.36	-	67.76	-

Appendix 4.10- CV of Influent TS, TSS

Table 9.7 *CV of Influent TS, TSS on different 8 day*

Day	CV of influents TS	CV of influent TSS
1	6.03	4.78
2	1.19	4.4
3	1.45	12.79
4	0.65	9.5
5	5.92	0.95
6	1.8	2.73
7	1.44	4.25
8	2.68	10.15
Average %	**2.6**	**6.2**

Appendix 4.11 CV of effluent TS of thickener

Table 9.8 *CV of effluent TS*

Day- influent flowrate (m^3 h^{-1})	CV of effluent TS
12-50	1
13-50	5
14-50	6
14-65	4
15-50	1
16-50	1
16-71	2
17-65	4
18-65	3
19-65	3
20-65	2
21-71	2
22-71	2
Average %	**2.77**