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A method developed for assessing anaerobic sludge dewaterability

Master's thesis in Environmental Engineering

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Department of Architecture and Civil Engineering
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Gothenburg, Sweden 2017

MASTER'S THESIS BOMX02-17-83

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Cover:

The building where the pilot study initiated in Rya wastewater treatment plant

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ABSTRACT

Sludge is a by-product generated from wastewater treatment process and can be further used as fertilizer. However, according to new regulation, better hygienization should be done for sludge treatment. One way to do this is by anaerobic digestion at thermophilic conditions (55ºC). Gryaab AB, the municipal company treating wastewater in the Gothenburg region, initiated a pilot study where the thermophilic and mesophilic (35ºC) anaerobic digestion as well as the transitory stages in between are studied and compared. This thesis work developed a pressure filtration test (PFT) method to evaluate the dewater-ability of sludge from the two-different digestion condition. The influence of polymer dosage, pressing time and hanging weight as the experimental conditions on the final dry solid (DS) results were investigated and the optimal configuration and operating procedure used for this method were recommended. Average DS results of 30.18% was obtained by this method and the repetitive experiments confirmed its reliability and feasibility with standard deviation of 0.297% and coefficient of variation of 1%. The capillary suction time (CST) method, was also studied but did not show the dewater-ability characteristics of the sludge.

Key words: sludge, dewaterability, CST, PFT, thermophilic, mesophilic

En metod som utvecklats för att bedöma anaerob slams avvattningsegenskaper

Yulang Guo

Institutionen för Arkitektur och samhällsbyggnadsteknik

Avdelningen för *Vatten- och miljöteknik*

Chalmers Tekniska Högskola

SAMMANFATTNING

Slam är en biprodukt som genereras av avloppsreningsprocessen och kan vidare användas som gödselmedel. Enligt ny lagstiftning (slamcertifieringssystemet REVAQ) bör dock bättre hygienisering göras för slambehandling. Ett sätt är termofil rötning vid 55 ºC. Gryaab AB, det kommunala företaget som behandlar avloppsvatten i Göteborgsregionen, initierade en pilotstudie där termofil och mesofil (35ºC) anaerob rötning samt de övergående stadierna däremellan studeras och jämförs. I detta examensarbete utvecklades en metod för tryckfiltreringstest som utvärdera den avvattning förmåga av slam från det två olika rötningsförhållandet. Inverkan av polymerdosering, pressningstid och hängvikt som testsförhållandena på halten torrsubstans (TS) i slammet undersöktes och den optimala konfigurations- och driftsproceduren som användes för denna metod rekommenderades. Genomsnittliga TS-resultat av 30,18% erhölls med denna metod och de repetitiva experimenten bekräftade dess tillförlitlighet och genomförbarhet med standardavvikelse på 0,297 % och variationskoefficient på 1 %. Metoden för CST-analys studerades också, men visade inte slammets avvattningsegenskaper. Detta examensarbete skrivs på engelska.

Nyckelord: slam, avvattningsegenskap, tryckfiltreringstest, CST, mesofil, termofil

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Yulang Guo, Gothenburg, June 2017

Nomenclature

	Description
WWTP	Wastewater treatment plant
DS	Dry solids contents
SS	Suspended solids
OLR	Organic loading rate
HRT	Hydraulic retention time
TS	Thermophilic sludge
MS	Mesophilic sludge
CST	Capillary suction time
PFT	Pressure filtration test
MBBR	Moving bed biofilm reactor
SRF	Specific resistance to filterability
EPS	Extracellular polymeric substances
VFA	Volatile fatty acids
VVS%	Volatile suspended solids
CV	Coefficient of variation
Eq.	Equation
SEK	Swedish krone

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1 Introduction

Wastewater, as mainly generated from municipal, agricultural and industrial water usage, has long been a major issue for sustainable development and environmental protection. Wastewater treatment plants (WWTP) treat wastewater and return it back to the water cycle. Nowadays WWTPs are facing the increasing burden from the growing population, and the knowledgeable public require more strict regulations to reduce the hazardous impact on the natural aquatic environment. Those factors are pushing the treatment process for innovation.

Sludge is a by-product generated from the wastewater treatment processes. It is mainly generated from the biological processes, and the more effective in removing contaminants from the waste water those processes are, the more sludge is produced. In fact, almost every WWTP's process chain ends with sludge disposal. It has been recognised that sludge management contributes to the major investment and operating costs in WWTP and technical challenges are formed in this area (Neyens, Baeyens, Dewil, & heyder, 2003).

One effective and widely used way to stabilize the WWTP sludge is anaerobic digestion, which can largely consume the organic matters in the sludge and generate bio-gas for energy compensation. The digested sludge could be an ideal fertilizer for farmland since it contains valuable nutrients like nitrogen and phosphorus. However, for farmland use, sludge has to be treated to avoid transmittance of pathogenic microorganisms. In Sweden, mesophilic digestion at 35-40ºC is the mostly common way to treat sludge (Gantzer, o.a., 2001), but according to the Environmental Protection Agency's new sludge regulation (Balmér, o.a., 2002), demands for hygienization of sludge are expected in the near future. An approved method for hygienization is thermophilic digestion (55ºC) at a solids retention time (SRT) of at least 8 hours (EC., 2001). According to the new regulations, many municipalities are considering to change the anaerobic digestion to thermophilic operational mode. For WWTPs, it is important to understand how a transition from mesophilic to thermophilic operation can be done while maintaining process stability, e.g. biogas production and sludge dewaterability. Gryaab AB, a municipally owned company running the wastewater treatment plant in the Gothenburg area, has therefore initiated a pilot-scale study where the thermophilic anaerobic digestion and mesophilic anaerobic digestion as well as the transitory stages in between are studied and compared. This thesis work, as part of the pilot-scale study, was implemented to develop a feasible method for assessing the sludge dewater-ability from different operational condition.

As one crucial character of sludge disposal, the dewater-ability reveals how well the moisture of the sludge can be reduced. Since sludge from WWTP is normally in liquid suspension and contains a large amount of water, it is important to reduce the total volume of sludge for the subsequent handling and financial saving. In 2016, 56000 tons of dewatered sludge with average dry solid content (DS) of 25.9% were produced at Rya WWTP. This represents 25 231 875 SEK from the company budget. An increase of DS in the sludge of 1.0% would represent a reduction of 95 5282 SEK for the company.

1.1 Description of Gryaab

"Rya" wastewater treatment plant (WWTP) is located on the northern side of Gothenburg, the second largest city of Sweden. Operated by the municipal company Gryaab AB, the plant serves about 830,000 PE in Gothenburg region and is one of the largest plants in Scandinavia, where 123 million cubic meters of water is treated annually (Gryaab AB, Årsredovisningen, 2016). The plant contains two streams, the wastewater stream and the sludge stream as illustrated in figure 1-1.

The wastewater flow varies between 2 to 16.5 m^3/s with an average daily flow of 4 m^3/s (Wilén, Mattsson, & Johansen, 2012). Bar screens, sand trap and primary settling tanks constitute the primary treatment of

the wastewater stream and the majority of solids are removed at this stage. Activated sludge tanks are used for denitrification and removal of organics, and are followed by the secondary settling tanks that collect and return the settled sludge. After that, the nitrification is realized in trickling filters and the first MBBR (moving bed biofilm reactor) process. The second MBBR tank works as supplementary to the activated sludge tank for denitrification purpose. Those biologic treatments constitute the secondary treatment for the plant. The tertiary treatment process consisting of 32 sets of disc filters, which contain micro-screens of 15µm of pore size, are used for final polishing of the effluent. Afterwards, the treated water is discharged into the river Göta Älv (Mattsson, Nivert, & Heinonen, 2012).

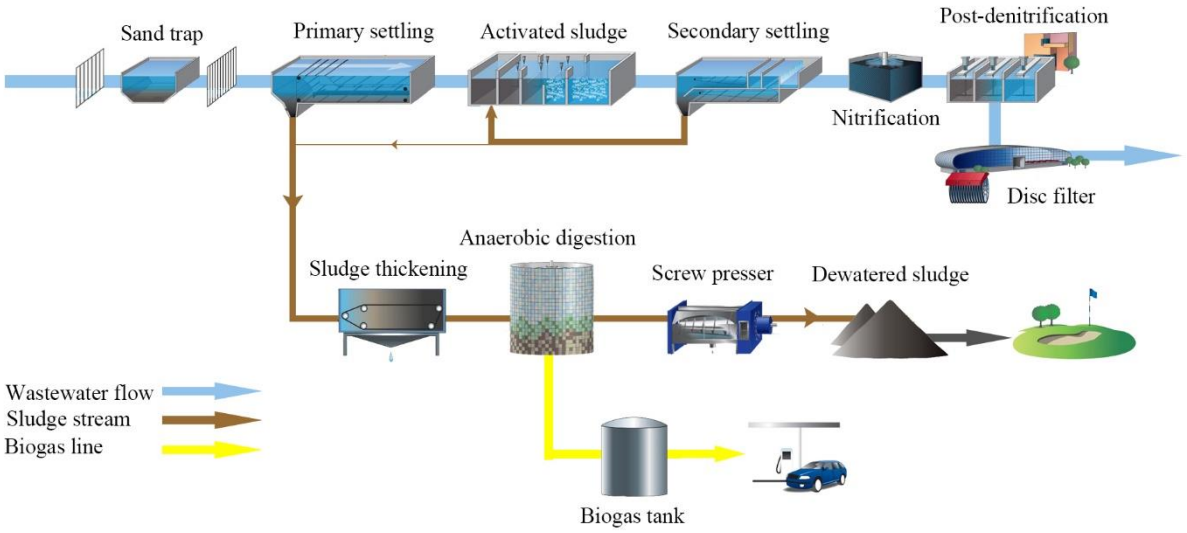


Figure 1-1: Schematic diagram of the Rya Wastewater Treatment Plant

The sludge stream starts at the primary settling tank to collect the primary sludge. Sludge from the secondary settling tank mostly returns back to the activated sludge tank but partly goes to the sludge stream. The sludge in the sludge stream is then thickened by a belt gravity thickening process with polymer (flocculants) addition, and subsequently goes to the anaerobic digestion tanks to generate bio-gas, see figure 1-2. It is worth to mention that extra biomass like fats, oils, grease and food waste from local restaurants and commercial kitchens also go into the anaerobic digestion tanks (Forgie, 2008) (Gryaab AB c. , 2010).

Figure 1-2: Anaerobic digestion tanks

The anaerobic digestion (mesophilic condition, 35 ºC) consists of three tanks, each tank represents one stage (raw sludge, medium-digested sludge, mature-digested sludge). Sludge goes through all three stages using 20 days (HRT). The whole process generates over 65 GWh of biogas. This value is almost twice the energy consumption for the Rya WWTP (Gryaab, 2013). Finally, the digested sludge is conditioned with polymer and dewatered by centrifuge process, for transportation and further disposal. In 2017, the centrifuge process has been taken place by the screw pressing device (figure 1-3), which slowly provides 3 bar pressure in the end of the device to press the sludge. The pressed sludge contains 70% of water (average DS 28%), which resembles the moisture soil, and more than half of the original organic stocks remains. From 2016, 23,500 tonnes of sludge were produced at the Rya WWTP and approved for agricultural use according to Swedish Water Certification System. (Gryaab AB, Årsredovisningen, 2016).

Figure 1-3: a) The old centrifuge process; b) The new screw pressing device

1.2 Pilot-scale study of anaerobic digestion

The pilot-scale study is being carried out in six reactors of 8 litres volume, see figure 1-4. The project takes place in four phases over a period of about 7 months. During those period of time, different operational conditions will be investigated in addition to gas production, sludge properties and the process stability.

Figure 1-4: Pilot-scale anaerobic digestion reactors

In phase 1 (starting phase), all reactors are operated in mesophilic condition for about 6 weeks, for around two hydraulic retention times, to give a stable platform for subsequent phases. In Phase 2 (temperature increasing phase) the temperature is increased in three of the reactors, from mesophilic condition (35 ºC) to thermophilic condition (55 ºC). The temperature is increased at different rates in the three reactors to evaluate the effect of the transition rates. In phase 3 of the trial, the three reactors that have achieved thermophilic temperatures will be compared with the three other reactors which are retaining at mesophilic condition. The organic and hydraulic loading on all reactors will be kept constant in the first three stages of the experiment. In phase 4, two of the mesophilic reactors and two of the thermophilic reactors will be gradually overloaded but in two various rates of escalation respectively to observe the influence of this on the process performance.

**The daily operation and maintenance of the reactors is carried out by the operator in Gryaab AB.*

2 Purpose and limitation

2.1 Objective

The main objective of this study is to develop a method for sludge dewatering tests. The developed method can be used for different comparison purposes. For example, to compare the effect of thermophilic and mesophilic operation, different polymer types, or other variables on the dewatering characteristics of the sludge. The developed method should give reproducible results, be efficient enough to be carried out in acceptable time frame, and feasible enough that operation can be implemented by any other tester.

There are two candidates of methods, which are pressure filtration test (PFT) and capillary suction time (CST). The present study relies on PFT and CST is used as a supplement method to compare with the results of PFT.

During the development of the PFT method, three key parameters of experimental condition are investigated to see their relationship with final DS result. They are polymer dosage, pressing time and hanging weight (see chapter 4 **Methodology**). Three assumptions have been made:

- The less polymer dosage that is added, the higher DS result can be obtained;
- The longer time the sludge has been pressed, the higher DS result can be obtained;
- The heavier weight that is implemented on sludge, the higher DS result can be obtained;

Also, a good DS result of the sludge cake and clean reject water quality are expected for the method developed. It is considered important from economic aspect for full-scale process operation, since high DS result represents less weight of sludge cake, so as to save transportation and handling fee; and good reject water quality can largely avoid the recycling process of reject water, so as to save energy and money for the WWTP.

2.2 Scope and limitation

- The literature review focuses on anaerobic digestion and previous studies on dewatering methods.
- The sludge properties vary because of the daily variation of wastewater quality. The quality difference between each day's raw sludge sample leads to differences in the results. Due to this fact, the focus is put on discovering trends of changes and comparing results between different experiment sets to get the conclusion.
- As mentioned, the measurement of sludge and polymer volume are inaccurate due to the stickiness etc., several ways to improve the experiment accuracy other than regular methods are investigated in this study.

3 Literature review

3.1 Anaerobic digestion

Anaerobic digestion is a wastewater treatment process where complex organic matters, i.e. polysaccharides, proteins and lipids, have been converted and decomposed to smaller organic compounds and further been digested by microorganisms under anaerobic condition. The mechanisms behind consist of several complex microbial processes, see figure 3-1, carried out by a wide range of bacteria and archaea, for example Clostridia, Synergistetes, Bacilli etc. The final products are methane and other gases like CO_2, H_2S, etc. It is a good way to generate biogas while cleaning sludge streams.

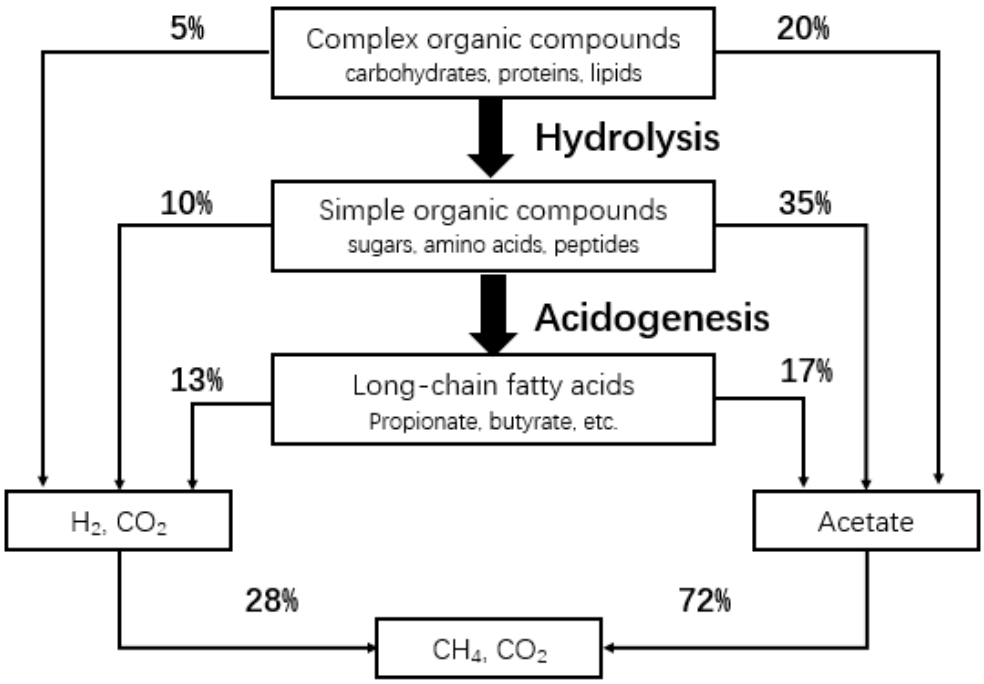


Figure 3-1: The patterns of carbon cycle in anaerobic processes, adapted from (Parthiban, 2012)

There are several limitations which affect anaerobic digestion. Since this process is carried out by microbes, microorganisms' living environment become very essential. Research shows that in a pH range of 6.5-8.2, especially near pH 7.0, anaerobic microorganisms can function ideally (Eckenfelder, 1999) (Speece R. , 1996). However, it is worth to mention that the whole process' pH is potentially decreasing since the acidogenic bacteria convert organic matter to organic acids (Rao, Senthilkumar, Feroz, & Byrne , 2012); also, two ranges of temperature have been proved to be effective for operation. Those are the mesophilic range (29°C–38°C) and the thermophilic range (49°C–57°C) (Eckenfelder, 1999) (Speece R. , 1996); In addition, operation factors such as organic loading rate (OLR), hydraulic retention time (HRT), solids retention time (SRT) and other nutrient concentrations for microbes are crucial in the process.

3.2 Sludge in anaerobic digestion

As mentioned, anaerobic digestion consists of several complex microbial processes, carried out by a wide range of bacteria and archaea. Previous studies (Dunn, Heinzle, Ingham, & Prenosil, 1992) (Quasim, 1999) (Speece R. E., 1983) have been conducted to research the different bacteria groups specialized in each process in details.

In the first step, organic polymers and lipids are hydrolysed to basic structural blocks, say amino acids, monosaccharides and related compounds. This process is conducted by the extracellular enzymes of obligate or facultative anaerobic bacteria such as Bacillus (degrading proteins and fats) and Clostridium (degrading cellulose and starch). Then, bacteria such as Peptococcus anaerobius, Desulfovibrio ssp., Actinomyces, Clostridium spp., Bifidobacterium spp., Staphylococcus, Escherichia coli and Lactobacillus, which are described as non-methanogenic in some literatures, ferment and break down organics into acetic acid. Lastly, the hydrogen and acetic acid are degraded into methane gas and carbon dioxide by methanogenic archaea such as Methanococcus and Methanosarcina (sphere-shaped) and Methanobacterium and Methanobacillus (rod-shaped). (Holland, Knapp, & Shoesmith, 1987) (Wiesmann, 1988)

Anaerobic sludge contains mainly organic substances and few inorganic substances. The organic part includes the microorganisms mentioned above and their metabolic products such as fatty acids, fibres, proteins, free amino acids and carbohydrates etc. The organic content can be measured by several criteria such as chemical oxygen demand, biochemical oxygen demand and total organic demand. The inorganic part contains nitrogen, phosphorus and heavy metals (Pb, Zn, Mg, Cu, Fe, Ca, etc.). (Gillberg, Hansen, Karlsson, Enkel, & Pålson, 2003)

Anaerobic sludge is bonded with different forms of water, see figure 3-2:

- The free water which is not attached to any particle.
- The surface bound water which is the water molecules that adhere to the sludge particle's surface by the force of hydrogen bonds.
- The capillary water which is mechanically bound between sludge particles.
- The cellular water which is the inner water of the microbes in sludge.

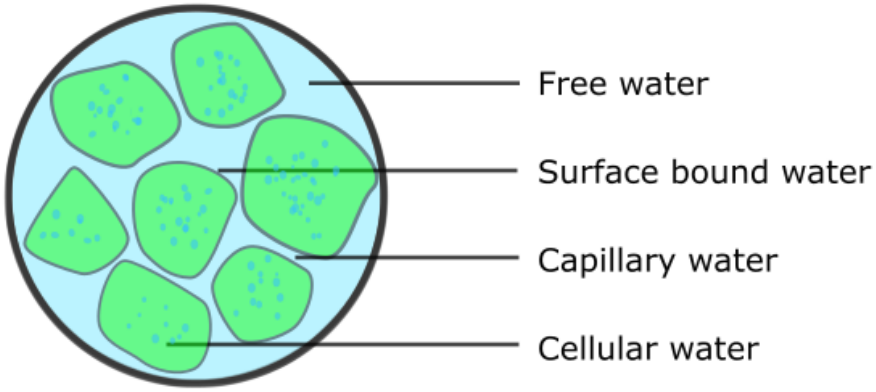


Figure 3-2: Illustration of different water forms in the sludge, adapted from (Texier, 2008)

Even though sludge contains large amount of water, it is hard to separate them out by simple means due to the jelly-like layer formation of the inner microorganisms that attracts the water strongly (Gillberg, Hansen, Karlsson, Enkel, & Pålson, 2003). Before the dewatering step, the sludge has to be conditioned so as to break down the jelly layer. Different means can be applied, such as lime and iron chloride, enzymes or chemical oxidative agent (Degrémont, 1991).

In Gryaab, cationic polymer is used as the conditioning agent. Polymer works as flocculants, which normally has high molecular weights and different molecular structure (linear, branched or cross-linked). As destabilized particles in the sludge are captured by the long chain of the polymer, the particles aggregate to form flocs with the release of water, and consequently realises the solids-water separation. Polymers have strong adsorption capacity (Lu, Pan, Hao, & Peng, 2014), and when they capture sludge particles, water is also trapped in the flocs which increases the difficulty of sludge dewatering (Zhang, o.a., 2017).

3.3 Mesophilic and thermophilic digested sludge

In the anaerobic digestion process, temperature is essential for microbial metabolic activities. It affects the overall digestion rate, particularly the rates of hydrolysis process and methane generation. There are two ranges of temperature used in the anaerobic digestion process nowadays. Those are the mesophilic range (30°C–43°C) with an optimum temperature of 35°C and the thermophilic range (48°C–60°C) with an optimum temperature at 55°C (De la Rubia, Riau, Raposo, & Borja, 2013).

Mesophilic anaerobic digestion is the most widely used system (Ros & Zupancic, 2003) (Horan, Fletcher, Betmal, Wilks, & Keevil, 2004) because of its stability and less energy requirement. Also, less risk of ammonia nitrogen toxicity is one of its many advantages. Thermophilic conditions allow anaerobic digestion to operate with higher OLR (organic loading rate) and lower HRT (hydraulic retention time). It provides higher efficiencies for organic conversion and better pathogen disinfection. It is more efficient in biogas production and volatile solid reduction, and class A bio-solids, a bio-solids that contains no detectible levels of pathogens (WEF, 2004), can be obtained by thermophilic condition if the time temperature criteria specified in the US EPA part 503 are met. In addition, it has better capacity with smaller reactor volume, resulting in lower financial cost. However, the drawbacks of thermophilic digestion are also obvious that higher energy and maintenance are needed. Odour problems and risks of thermal shock are also reported. (De la Rubia, Riau, Raposo, & Borja, 2013) (theecoambassador, n.d.)

There are two voices arguing on the dewater-ability of sludge digested under thermophilic condition. Some studies have referred that thermophilic sludge has better dewater-ability (Garber W. , 1954) (Garber W. F., Operating experience with thermophilic anaerobic digestion, 1982) (Garber, Ohara, Colbaugh, & Raksit, 1975) (Rimkus, Ryan, & Cook, 1982) (Peddie, Tailford, & Hoffman, 1996). Some other yet pointed out that the thermophilic process increases the difficulty of dewatering since up to 10 times more extracellular polymeric substances can be produced under thermophilic condition comparing to mesophilic digestion (Fischer & Greene, 1945) (Smart & Boyko, 1977) (Kugelman & Guida, 1989) (Chi, o.a., 2010) (Zhou, Mavinic, Kelly, & Ramey, 2002). The reason of argument can be attributed to the different methods implemented in those studies to determine the parameters and processes of sludge dewatering (De la Rubia, Riau, Raposo, & Borja, 2013). Despite of those arguments, it is still believed that the quantity of disposed sludge can be reduced by 30-40% by using thermophilic digestion, since the dewatered sludge tends to have higher solid content, in combination with the fact that higher solid reduction can be obtained by thermophilic digestion.

3.4 Sludge pressure filtration method

The main stream press method for sludge dewatering in large scale operation is the pressure filtration device, see figure 3-3, which uses hydraulic or mechanical forces to press the sludge. It is structured by several plates with filter chambers in between. On the one side of the device is a fixed end, on the other side is the travelling end. When it operates, sludge liquid fills into the filter chamber and the travelling end moves toward the fixed end to push the plates. Sludge in the filter chamber is squeezed, and consequently reject water pass through the filter and solids are remained in the chamber. The feeding process stops until the chamber is full of sludge cake, by then the travelling end removes and the plates open to let the sludge cake fall out. The reject water flows away through the drainage system and sludge cakes are collected by a conveyor for the transportation. The pressure filtration method provides 225-250 PSI (approximately 15-17 bar) on the sludge and results in 36-60% DS content depending on the conditioning agents (Degrémont, 1991).

Figure 3-3: The commonly used pressure filtration device, picture from (Ecologix Environmental Systems, 2017)

Previous experimental studies on the sludge press method have been conducted. Pierre Texier (2008) used a method developed by Kemira Kemi AB. It consisted of a filtration step, a pressing step and a drying step. In the filtration step a Büchner funnel was used for vacuum filtration (figure 3-4-a), and sludge was filtered through two filter paper (9cm in diameter). After filtration, the weight of sludge cake along with two filter paper was measured as m_a, then the weight of one filter paper was also measured as m_b. Thus, the weight of the sludge cake filtered was calculated as $m_c = m_a - 2 \times m_b$. In the pressing step, two other filter papers with the same size as the previous two were covered on the sludge cake filtered in the previous step, along with those two old filter paper underneath the sludge cake. Then five bigger filter papers (12 cm in diameter) were place above it and underneath it respectively (ten papers in total) to form a pre-pressing ensemble, see figure 3-4-b. The ensemble was pressed by a metal press device with 20kg weight for 10 minutes. After the pressing process, the weight of sludge cake along with two filter papers that covered it was measured as m_d. Also, the weight of two other filter papers of the same size was measured as m_e. Then the weight of sludge cake pressed was calculated as $m_f = m_d - m_e$. The last step was a drying step in an oven at 105°C. The sludge cake along with two inner filter papers attached was dried and weighed as m_g, and then the two-outer filer paper of the same size was dried and weighed as m_h. Afterwards, the weight of sludge cake dried was calculated as $m_i = m_g - m_h$. Finally, the dry solid content of the sludge after filtration and pressing were calculated as $DS_{filtr} = m_i / m_c$, $DS_{press} = m_i / m_f$.

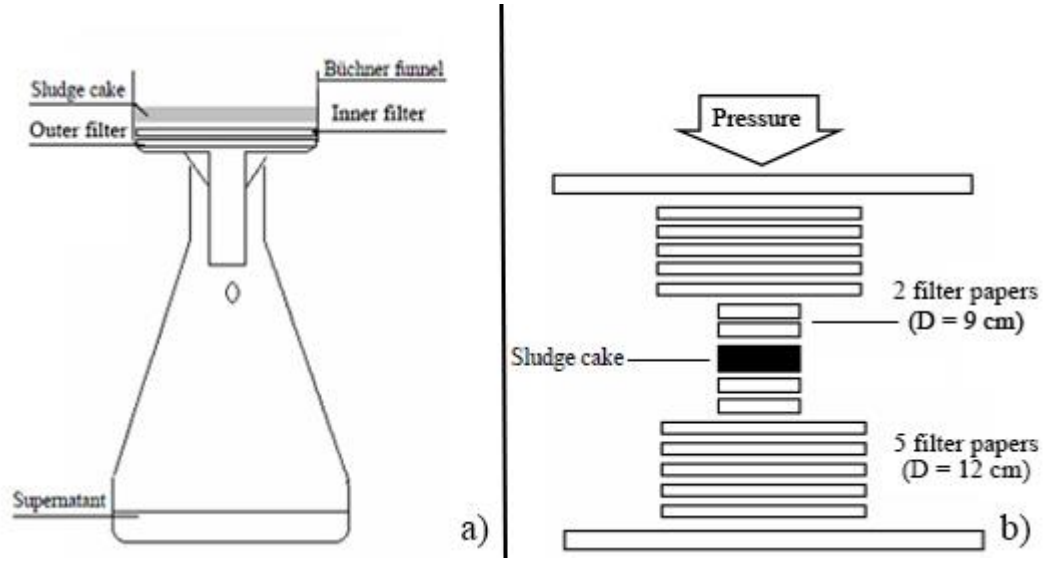


Figure 3-4: Schematic pictures of Texier's experiment, adapted from (Texier, 2008)

Sludge conditioning was not included in the method Texier used. On the other hand, it assumed that all the filter papers in the same size have the same weight. It is uncertain if non-negligible error was made through this assumption, since experiments were done in small weight dimension (around one gram of total solids as described). In addition, it is written that when the lab result was compared with full scale process, the R^2 coefficient was a high value of 0.89 (Texier, 2008). So, it was concluded that this method cannot be a prefect prediction for full scale dewatering (centrifuge) process. This study also compared the average values of DS_{press} and its 90% confidence intervals under two different experiment temperatures (25°C and 8°C). The results were significantly similar, so the conclusion was drawn that temperature (between 8 and 25°C) has no significant influence on the DS_{press} at a fixed pH.

Another study using ultra-high pressure filtration system to investigate the dewater-ability of five different sewage sludge with different organic matter content was conducted in Guangdong University of Technology, China (Liang, Huang, Dai, Li, & Sun, 2015). The study investigated, among others, the relationship between SRF (specific resistance to filterability), EPS (extracellular polymeric substances), the bound water contents and the VVS% (volatile suspended solids) character of sludge, associated with the dewater-ability. It revealed that sludge with high VSS% contains higher concentrations of EPS and bound water, which limited the dewater-ability of sludge, and inversely low VSS% sludge has faster and easier dewater-ability. The mechanism of the ultra-high pressure filtration system involved sludge conditioning with Fenton's reagent and lime, pumping sludge into the spring filter press by piston pump, pressing sludge with increasing the pressure from 1.6Mpa to 40Mpa, and final collection of filtrate and sludge cake. Despite of the advantage that it can be used in a good way to mimic the full-scale pressure filter process efficiently with a pressure controller. This method was considered to be too complicated and costly for current study, since it consisted of several apparatuses like conditioning tank, piston pump, pressure controller and the two-stage compression device, and it was designed for dealing with large volume (100L) of sludge.

A method originally developed by Gryaab AB was finally decided to be used in this study, see chapter 4.1.1.

3.5 CST method

The Capillary suction time (CST) test is a commonly used method to measure the filterability and the easiness of removing moisture from slurry and sludge (SAWALHA & SCHOLZ*, 2007). The test measures the time for free water to pass through a certain distance using suction paper as the medium. There are two voices toward CST method. One said the CST method has long been built as the leading method for sludge dewatering test, for its feasibility, efficiency and the cost-saving. It could be accurate if the specific resistance to filtration and solid concentration is of interest (Scholz, 2005). However, another study has pointed out that CST method could not be directly used to analyses the bound water in the sludge (Chen, Lin, & Lee, 1996). On the one hand, the bound water is a badly defined quantity which varies with the measurements; On the other hand, the bound water would move together with the sludge solid phase when the experiment was done, making it hard to interpret the particle concentration of the sludge. Although massive experiments have been conducted for CST test as one of the parameters for sludge conditioning and dewaterability, see *Review of Recent Trends in CST Dewaterability Testing Research* (Scholz, 2005), empirical knowledge is limited regarding specific polymer types used in Rya WWPT as well as the thermophilic sludge of interest. In this study, the CST method was used on the one hand to compare the permeability of different sludge to reveal their dewatering effect; on the other hand, to help developing the pressing method to reveal the relationship of polymer dosage, pressing time and hanging weight.

4 Methodology

The contents of work for the present study included inspection of the pilot reactors, sampling and lab analysis of sludge, collection and interpretation of data. For evaluation of the dewatering characteristics of sludge, two different methods were implemented which are **Capillary suction time** (CST) method and **Pressure filtration test** (PFT). The experiments were mainly conducted with the PFT method. CST was used as a supplement and for comparing with the results of the PFT method.

The PFT method involved pressing a sample of sludge against a fine meshed wire screen with pore opening of 0.55mm, and consequently separating the filtered water (also referred as reject water in the following text) and the sludge cake. The PFT method mimicked the large-scale sludge compressing process and to a certain extent revealed the final effect for the compressing process. During the PFT method, the following were analysed:

- Amount and type of polymer applied before dewatering.
- Pressure applied across the filter during the dewatering.
- Time of dewatering.
- Dry solids content of the sludge before and after dewatering.
- Volume of reject water.
- Sludge solid (SS) in the reject water which penetrated the filter during the pressing process.

The experiment work was divided into two stages. While all the pilot reactors were operated in mesophilic condition, the first stage was to develop a feasible method that could be implemented in the following mesophilic and thermophilic comparison experiment. It took a large number of trial and error experiments to improve the method in order to get reliable and repeatable results. Development included modification of the pressing device, detection and elimination the human error, formulation of the right procedure for doing the experiment.

During the first stage, the relationship between three key variables and the final DS results were discussed. They were polymer dosage, pressure and pressing time.

- The polymer dosage was the amount of polymer added according to the amount of sludge solids in the sludge liquid (raw sludge concentration). The unit for polymer dosage was g polymer/kg sludge. In the following text, the unit is skipped and represented as dosage value (e.g. dosage 11). The purpose of adding polymer was to coagulate the sludge solids and separate the reject water out, so as to make sludge dewatering easier. It was also called sludge conditioning.
- The pressure was the force that was implemented on the sludge in order to press the water content out. It was a force provided by a constant weight for each experiment, represented as kg. Several sets of weight have been tested in order to discover the trend and relationship with DS result.
- The pressing time was the time counted after the weight had been set on the pressing device. Different time sets were tested in order to discover the trend of time effect on dry solids result. The unit for pressing time was minutes.

The three variables were independent from each other but all have direct impact on the final DS results. The way of testing was to give different sets of experiments for different factors. While doing one test

two other factors was kept constant. The order of doing them was not important, as far as the results of each factor revealed a trend (or relationship). Then, the optimal condition of each single factor experiments was set as the next test's condition until the ideal combination of configuration was discovered for the next stage's comparison study.

The second stage was based on the developed method to do the comparison experiments between mesophilic sludge and thermophilic sludge to find the DS difference. However, due to time frame issue that mature thermophilic sludge was not obtained till the end of the thesis study, only one experiment was done for comparison of the immature thermophilic sludge and the mesophilic sludge from pilot reactors.

The CST test was implemented at the first stage of experiment as a complement for PFT method. It measured the filtration rate of free water which passed through two electrodes as the trigger for time counting. It was scheduled to use the CST method on the one hand to test the permeability of different raw sludge to reveal their dewatering effect, and on the other hand to examine the dewatering characteristics of the products produced by the PFT method. In order to make the best benefit of CST method as scheduled, it was used at three point of the development of the PFT method. First, the raw sludge liquid was tested by CST method to show the dewatering characteristics of raw sludge. Then the sludge complex, which was the sludge chunk formed by mixing with polymer agent, was tested to reveal the dewatering effect of different polymer dosage. Lastly, the sludge cake formed by pressing was tested, to reveal the different effects of different pressing time or hanging weight.

4.1 Instruments and use recommendation

4.1.1 Pressing device (Developed by Gryaab AB)

Figure 4-1: The pressing device used in current study
1. Presser cap; 2. Filter (Mesh opening 0.55mm); 3. Vessel; 4. Basin; 5. Lever; 6. Hoister; 7. Weight

Principle:

This pressing device, see figure 4-1, was manufactured by Gryaab AB, aiming at pressing the water out of the sludge, resulting in the formation of a sludge cake. To install the device, the basement of the device was set and fixed on the table. The basin was used for collecting the reject water. It was screwed into the base and could be detached to pour the reject water into the conical cup. The vessel with a baffle inside was the container for the sludge. The inner diameter of the vessel was the same as the filter used. The vessel was set in the basin using a simple mechanism to attach and detach. When the experiment was done, the filter was set on the baffle in the vessel and the sludge was poured into the vessel. The sludge should be evenly spread on the filter and then the presser cap was slowly and smoothly pressed down to the filter to compress the sludge. The weight was hanging on the lever to provide the pressing force. The weight was gradually loaded by the hoister to guarantee a smooth process.

The relationship between the pressure and the weight was illustrated by Eq. 4-1, 4-2, 4-3, and figure 4-2.

$$F_1 * X_1 = F_2 * X_2; \quad (4\text{-}1)$$

$$F_1 = W * g \quad (4\text{-}2)$$

$$P = F_2/(\pi * (d/2)^2); \quad (4\text{-}3)$$

W – Weight, kg;

g – Gravitational acceleration, 10N/kg;

F_1 – Force provided by weight, N;

F_2 – Force working on sludge, N;

X_1 – The length of the lever, m;

X_2 – The length from pressure point to the supporting point, m;

P – The pressure acting on the pressed sludge, Pa;

d – The inner diameter of the vessel, m;

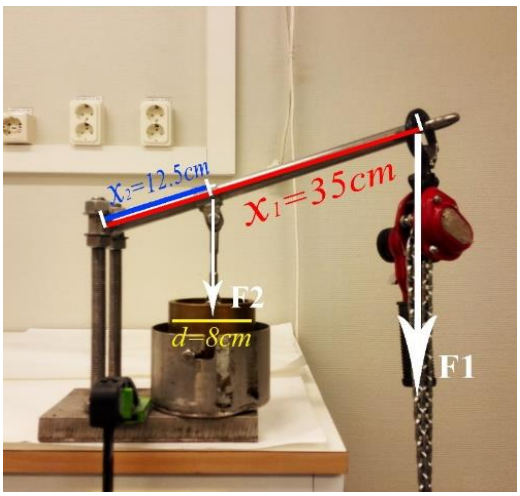


Figure 4-2:
The mechanical schematic diagram of the device

4.1.2 CST timer (Triton, 304M)

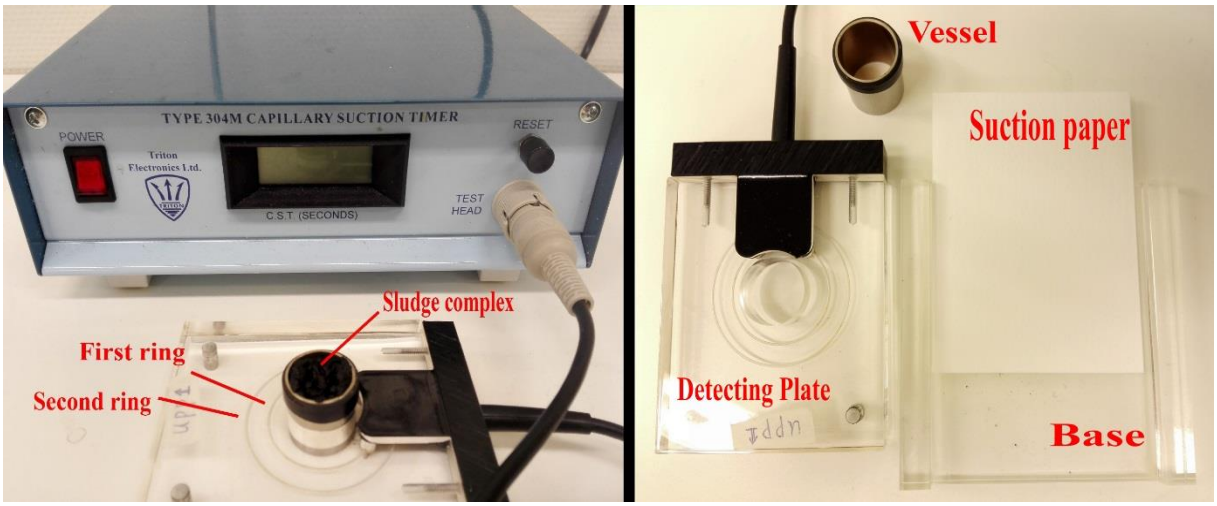


Figure 4-3: The CST timer used in current study

Principle:

The capillary suction timer, see figure 4-3, was used to measure the easiness of the water which can be sucked out from the sludge, which could from another aspect represent the sludge dewater-ability.

To perform the experiment, the suction paper (Whatman No.17) was placed on the base and covered by the detecting plate. Then the small metal vessel was set in the middle hole of the detecting plate. The device was turned on by switching the power button and then the reset button was pressed once. When the sludge was filled in the metal vessel, water in the sludge was sucked out by the suction paper underneath. The time taken for the water pass through two electrodes constitutes the CST. The suction force is considered larger than the hydrostatic head within the vessel, so the test is relatively independent from the sludge volume inputted, as long as the volume is sufficient to conduct the measurement (Scholz, 2005). By comparing the time difference, the easiness of dewatering characteristic for different sludge was revealed. The less the suction time obtained, the faster the water spread, which meant the sludge had better filterability.

4.1.3 Dryer (Sartorius, MA-35)

Figure 4-4: The dryer used in current study

Principle:

The dryer consisted of two parts, see figure 4-4, one dryer machine with operation panel and indication screen, one printer which printed out the results on the paper. The dryer machine contained an oven that provided a constant 130°C temperature environment as to dry the water out from the sludge. The DS result represented the weight percentage of the dried sludge from the original sludge cake or the sludge liquid, the unit was % (see Eq. 4-4). When the experiment was done, a plate was placed in the oven and the weight was cleared to zero. Then amount of sludge cake or sludge liquid was put on the plate. Followed by closing the oven, the dryer started to heat the sludge automatically. After the water and moisture had been dried out, the screen indicated the DS result and the printer recorded the date, the original sludge weight, the dry sludge weight and the DS result on the paper.

DS (%) = weight of dried sludge (g) / weight of input sludge (g) (4-4)

4.1.4 Scale (DeltaRange, PM2500)

Figure 4-5: The Scale used in current study

For weighting, Mettler PM2500 scale was used (figure 4-5). It provided three decimal digital accuracy, the unit was g. In order to weigh the subject's weight, the container was firstly placed on the central scale and the weight was cleared to zero. Then the subject was filled in the container and scaled. At this point, the screen shown the net weight of the subject.

In this study, due to the viscosity of sludge and polymer, a few liquid drops constantly clung to the wall of the beaker or cylinder, see figure 4-6, it was hard to pour out liquid completely, resulting in inaccuracy of measurement. Thus, the method for measuring the volume by cylinder was improved to measure the subject's weight directly in the beaker. For example, in order to add 20ml polymer solution into 100ml raw sludge liquid, beaker was firstly placed on the scale and the weight was cleared to zero. Then sludge was slowly poured into the beaker on the scale. The addition stopped at the point that the scale revealed 100g. Then the weight was cleared again. The next step was slowly adding polymer solution directly into the beaker and stopped at the point that the scale revealed 20g. It was assumed that water had the density of approximately 1kg/L and the raw sludge and polymer had the density close to water. The assumption was made because raw sludge normally had DS result of around 3.5% (see chapter 5), which meant 96.5% of sludge content was water, and the used polymer concentration was 2g/l (see chapter 5.1.2), which meant 99.8% of the agent was water. Another advantage of this measurement method was the simplified calculation for polymer dosage, of which unit was g poly/kg sludge. The step of unit conversion between volume and weight was saved (see chapter 4.2.2).

Figure 4-6: The stickiness of the sludge

It is worth to mention two things here. Firstly, since the scale is very sensitive so it should be placed in a place without interference. Most lab place the scale in a ventilation cupboard and the flow of air causes a large numerical fluctuation, making it hard to read the value. In this study, the scale was placed in a static environment. Secondly, the drying factor should be put into consideration, since the atmosphere was very dry in Sweden. When the experiments were implemented, it was observed that 0.29g weight of water was lost during 30 minutes of exposing in the air, and 0.5g of sludge was lost during 30 minutes

of exposure. That was why the reading of the scale kept dropping once the beaker with liquid was set on the scale. So, the experiments should be done quickly in order to minimize the error.

4.1.5 Stirrer (Ikamag Reo)

Figure 4-7: The stirrer used in current study

Ikamag Reo magnetic stirrer was used for stirring, see figure 4-7. It gave a variety of stirring speed options from 100 to 1100 rpm (rotation per minute). By providing magnetic field that interacted with the magnetic rob inside the beaker, it made rob spun in the solution so as to mix the agent. The stirrer was mainly used in making polymer solution from standard agent.

It is worth to mention that aeration was observed during stirring. After long time and high speed stirring, many micro air bubbles were formed in the polymer solution. If aeration as well as high-speed stirring affect polymer's structure and character was unknown. However, since the purpose of this study was to investigate the tendency and make comparison, instead of getting an accurate numerical result (see chapter 2.2), and all the experiments used the same polymer making procedure, so this concern was ignored. Lastly, attention should be paid during the operation that the contact of spinning rob with beaker's wall might cause damage to the fragile glass wall.

4.1.6 Other instruments

Figure 4-8: Other instruments used in current study
1. Plastic Bucket I (2.5L); 2. Plastic bucket II (1L); 3. Plastic Bucket III (500ml); 4. Cylinder (100ml±1ml); 5. Small beaker (150ml); 6. Large beaker (500ml); 7. Syringe (10ml), 8. Syringe (1ml), 9. Spoon, 10. Tweezers. 11. Conical cup (1000ml).

Several other instruments were used during this study. The plastic bucket I and II was used for sludge sampling from full-scale process and pilot-scale reactors and their storage. The plastic bucket III was used for standard polymer agent storage. Cylinder was used for volume measurement in the beginning of the study. Small beakers (150ml) were used for making polymer solution for one day usage. Large beakers (500ml) were used for measuring raw sludge and the mixture of sludge and polymer. Syringe (10ml and 1ml) were used for accurate addition of liquid. As mentioned before (see chapter 4.1.4), both sludge and polymer were measured in weight (g) instead of volume (ml). To use syringe for liquid addition, it was observed that one drop of liquid from 1ml syringe approximately equalled to 0.015 g (figure 4-9) and one drop of liquid from 10 ml needle approximately equalled to 0.04g. As a result, the accuracy of scale measurement method could be improved to 0.01g±0.015g by using syringe. The spoon and tweezers were used for collecting the sludge residual. The conical cup (1000ml) was used for measuring the volume of reject water and the sludge solid inside. The SS was read by the volume ratio of ml sludge solid/ ml reject water, unit %. In addition, stirring stick was used with conical cup, considering sometimes flocs last in the reject water and did not settle down. The stick was used to break floc's floating structure and make them settle down.

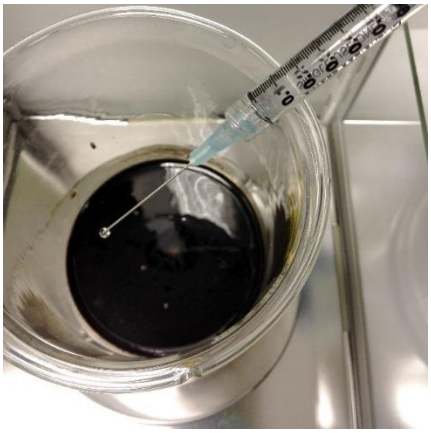


Figure 4-9: The way of adding polymer by syringe

4.2 Sludge sample and polymer agent

In order to implement the experiments, raw sludge sample and polymer solution were needed. This section introduces the sludge sampling and the making procedure of polymer solution and their storage.

4.2.1 Sludge

As mentioned in the beginning of this chapter, the study was divided into two stages. At the first stage (method development stage), the raw sludge samples were taken from the last anaerobic digestion tank of the full-scale process (see figure 1-2) by the plastic bucket I. They were fully digested and all in mesophilic condition. The regulation of sampling was once per experiment day. It means that each day's experiments were based on one sludge sample taken from the site. The sludge sample was stored in the plastic bucket for the whole day at room temperature. The sampling regulation and storage principle were also applied to the second stage (comparison stage). At the second stage, both mesophilic and thermophilic sludge samples were taken from pilot-scale reactors (see figure 1-4) by plastic bucket II. The reason for why sludge samples at the first stage were not taken from pilot-scale reactor was because in the beginning of this study the pilot-scale reactors were not ready. During that period of time, most of the pilot reactors' bio-system were just built up and were not in stable condition. Due to this reason as well as the consideration for the continuity of all the experiments did for the first stage, the samples were taken from the full-scale process tank No.3.

Two issues were taken into consideration for sludge sampling and storage. The first was the daily differences of the sludge quality. Each day's raw sludge condition was supposed to be different due to the source variation. For example, rainy days' sludge condition was different from dry weather day's sludge because of storm water influent, etc. It might cause differences in DS results of different experiment days, even if all the experimental conditions were the same. However, as mentioned in scope and limitation (chapter 2.2), the purpose of this study was to investigate the influence tendency for each experiment parameter affecting the DS result at the method development stage, and the different dewatering behaviour between mesophilic and thermophilic sludge at the comparison stage. So, the results based on one sample could give an idea to improve the method and make the comparison. Due to this consideration, the study was divided into several experiment days. Each day's experiments were isolated from other days but association could be found if experimental conditions were similar, so as to make the horizontal comparison. On the other hand, several experiments were done within one day using the same sludge sample to provide vertical comparison. Table 4-1 provides time series relating to experiment dates, as a reference for chapter 5 **Results**.

Table 4-1: Time series of experimental days throughout the study

Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 9**	**Day 10**
26-jan	27-jan	01-feb	03-feb	06-feb	08-feb	10-feb	13-feb	17-feb	20-feb
Day 11	**Day 12**	**Day 13**	**Day 14**	**Day 15**	**Day 16**	**Day 17**	**Day 18**	**Day 19**	**Day 20**
24-feb	27-feb	03-mar	17-mar	20-mar	27-mar	29-mar	10-apr	12-apr	19-apr
Day 21	**Day 22**	**Day 23**	**Day 24**	**Day 25**	**Day 26**				
26-apr	27-apr	03-maj	04-may	05-may	11-may				

The second issue was the degradation of sludge characteristic after storage, because of environment change such as aeration (sludge was not stored in completely anaerobic condition) and reduced temperature (from mesophilic or thermophilic temperature to room temperature). However, due to the lab condition, this problem was not tackled. Potential solution for this issue is discussed in chapter 7.

4.2.2 Polymer agent

In the experiments, polymer agent (Type Z8180 from BASF AB) was used to flocculate the sludge. Sludge complex (a complex of sludge, water and polymer) was formed after polymer addition. With right amount of polymer added, the majority of reject water was separated from the sludge, the rest water was still bonded in the sludge complex, see figure 4-10-b.

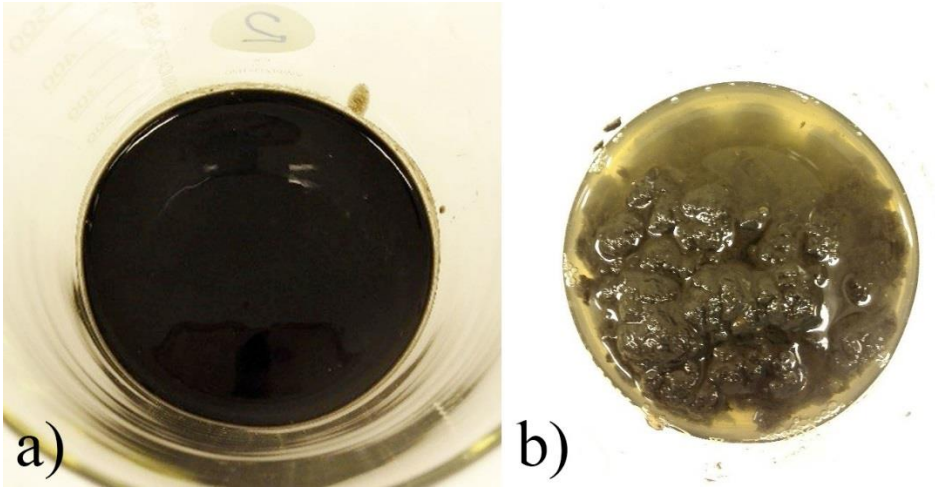


Figure 4-10: a) Raw sludge liquid; b) Sludge complex and reject water

In the first few weeks of experiments, the polymer agent was taken from the full-scale process (same polymer source for full-scale dewatering process) and the concentration was said to be 2 g/l. However, the polymer concentration from full-scale process turned out to vary from 1.8 to 2.6 g/l (see figure 5-2 in **Result** part). It gave large error to the experiment's results and misguided the tendency judgement, further description see chapter 5.1.2. To increase the accuracy of the experiments, it was decided to make a 2 g/l polymer solution from the standard polymer agent which had a constant concentration of 5 g/l. The standard polymer agent was provided by the polymer manufacturer from BASF. The principle was to make a certain amount of polymer solution for one day usage according to the volume of sludge sample tested that day. Eq. 4-4 was used to decide how much polymer solution was needed for one experiment. Then the total volume of polymer solution needed for that day was known by summing up each experiment's volume.

$$V_{polymer} = {W_{Sludge} \times C_{sludge} \times D_{polymer}} \Big/ {C_{polymer}} \quad (4\text{-}4)$$

Vpolymer — Volume of polymer solution needed, ml;

Wsludge — Weight of sludge tested, g; [1]

Csludge — Concentration of Raw sludge, g dried sludge /g raw sludge; [2]

Dpolymer – Polymer dosage, g polymer/kg dry sludge solids;

Cpolymer — Polymer concentration, g/l;

1. It is worth to mention that before day 15, raw sludge were measured in volume (ml), and then converted by $W_{sludge} = V_{sludge} \times \rho_{sludge}$. That is why in chapter 5 ***Results****, some tables use ml as raw sludge unit, and some use g. ρ_{Sludge} was calculated by using the weight of sludge divided by its volume, which was a repeated step. After day 15, W_{Sludge} was measured directly.*
2. The concentration of raw sludge, C_{Sludge}, was the DS result of raw sludge liquid and the unit was %.

Once the total volume of polymer solution was calculated, the next step was to make the polymer solution by diluting the standard polymer agent, using Eq. 4-5.

$$V_{PS} \times C_{PS} = V_{SA} \times C_{SA} \quad (4\text{-}5)$$

VPS— Total volume of polymer solution needed; 1

CPS— Concentration of polymer solution;

VSA — Volume of standard agent needed;

CSA— Concentration of standard agent, 5g/l;

1. V_{PS} equal to the sum of $V_{Polymer}$ (Eq. 4-4) of one experiment day.

The procedure of making 100ml 2g/l polymer solution was demonstrated below as an example, where100ml and 2g/l could be any volume and any concentration as needed for that experiment day. By Eq. 4-5, it was calculated that 40ml 5g/l standard polymer agent was needed.

1) 100 ml distilled water was prepared in small beaker 1.[1]
2) The standard polymer agent was taken out from the refrigerator and around 50ml poured into small beaker 2.
3) Blank small beaker 3 along with the magnetic stirring rod inside was weighed on the scale and clear to zero.
4) 40ml 5g/l standard polymer was measured into beaker 3 by syringe.
5) 60ml distilled water was measured into beaker 3 by cylinder.
6) Beaker 3 was placed on magnetic stirrer, stirring the solution in 1000 rpm for 2 minutes.

7) Ready.[2]

1. All liquid was measured in g instead of ml, as motivated in chapter 4.1.4.
2. When the polymer solution was ready, the solution revealed as homogeneous with few small air bubbles uniformly spread in the solution, which was caused by blending.

Regarding the storage, the standard polymer agent was stored in a dark and cold environment, in a refrigerator in this study. It expired in one month after the manufacturer sent it. The polymer solution made for daily usage was kept in a dark environment, say the lab drawer, and covered by plastic wrap to avoid the drying factor from the air.

4.3 Experiment procedures

This section introduces the experiment steps did for PFT and CST test in this study.

Preparation

1) The raw sludge sample was taken from the site.
2) Around 10g raw sludge was dried in the dryer to get the DS concentration of raw sludge.
3) The total volume of polymer solution needed was calculated according to the experiment plan of that day.
4) Polymer solution was made by diluting the standard agent (see chapter 4.2.2).
5) The storage bucket was slightly shocked to make the raw sludge liquid even from the settlement, then around 200ml was poured into beaker 1 for experiment use.

Pressure filtration test

1) 100 ml raw sludge was measured from beaker 1 to beaker 2. [1]
2) Polymer solution was added into sludge by syringe.
3) Sludge and polymer were mixed between beaker 2 and beaker 3 twelve times. [2]
4) The filter was weighed and then set in the vessel.
5) The sludge mixture was poured into the vessel.
6) The presser cap was slowly closed and pressed and then the weight and timer was set.[3]
7) After timer was over, the weight was taken off.
8) Then the vessel was taken out from the basin and the collected reject water in the basin was poured into the conical cup.[4]
9) After the basin and vessel were installed back, the presser cap was lifted up and the formed sludge cake was taken out with the filter and weighed together.[5]
10) Then 10g of sludge cake was scratched into the dryer plate for drying.[6]
11) After the sludge solid in the reject water was settled, about 10mins, the SS result was read from the conical cup and picture was took.
12) The DS result was recorded after the drying process was finished.
13) The devices were cleaned and reinstalled after the experiment was done.

1. All liquid was measured in g instead of ml, see chapter 4.1.4.
2. It was said by the polymer manufacturer that certain amount of mixing times could have the best effect. It was observed that the effect of mixture with twelve times was better than ten times. Further discussion can be found in chapter 6 ***Discussion.***
3. The polymer added, the pressing time and hanging weight in step 2) and 6) were adjusted according to the experiment plan of that day.
4. In step 8) and 9), the reject water was poured out first, then the presser cup was lift up from the vessel, to avoid vacuum suction which drew the reject water back to the sludge cake, see chapter 5.1.3.
5. From step 4) and 9), the weight of sludge cake was calculated, $W_{sludge\ cake} = W_{sludge\ cake\ +\ filter} - W_{filter}$.

6. It was around 10g. It didn't affect the final DS result that how much weight of the cake was dried, because the DS result was calculated by the machine using the weight difference before and after drying, see chapter 4.1.3. 10g was chosen due to time issue, since the more sludge dried, the longer time it took.

Capillary Suction time test

1) 50 ml raw sludge was measured from beaker 1 to beaker 4.
2) Polymer solution was added by syringe.
3) Sludge and polymer were mixed between beaker 4 and beaker 5 twelve times.
4) One filter was set on a small beaker (150ml), and the sludge mixture was poured on the filter. After the majority of water was filtrated, about 2 minutes, certain amount of sludge complex on the top was took for the CST test.[1]

1. These steps were done for CST test of the second point, to test the dewater-ability of the sludge complex (see the introduction of CST method in the beginning of this chapter). For the first point and third point of the test, the raw sludge liquid and sludge cake were directly tested by the CST device. Here, certain amount of sludge complex means the amount of sludge complex to fulfil the metal vessel of the CST device.

5 Results

Since the thesis work was to develop a method for testing sludge dewater-ability, the process consisted of numerous experiments to find out the right way of performing the method. There existed many unknown and errors during the development, in other words, the results and improvements were obtained and processed successively. In this chapter, the results are divided into three parts, where the first section gives out the main problems experienced during the experiments, and highlights the main changes done to improve the methods. The second section sorts out the influences of different experimental conditions on the PFT method. The last section presents results for CST method and other experiments that were relevant to this study. The daily experimental data can be found in appendix III.

5.1 Failed experiments and major improvements

Before the presentable results came out, there were several experiments which had been done with random results obtained. This section lists out those representative failures and analyses the causes behind.

5.1.1 To decide the usage of raw sludge volume

The experimental conditions for the first two days was shown in table 5-1.

Table 5-1: Experimental conditions of Day 1 and Day 2

Experimental conditions	Day 1		Day 2	
Raw sludge volume	50	ml	40	ml
Raw sludge density	1	kg/l	0.96	kg/l
DS of raw sludge g/g	3.56	%	3.6	%
Polymer concentration	2	g/l	2	g/l
Hanging weight	10	kg	10	kg
Pressing time	15	min	15	min

In the first two days of experiments, one small pressing device was used. It had half size of the device shown in figure 4-1, with vessel and basin that could press raw sludge less than 80ml. The first day 50ml of raw sludge was used and the second day 40 ml was used, to determine the effect of different raw sludge volume on the DS results. In day 1, sludge density was assumed to be 1 kg/l, due to the factor

that the majority of sludge was water content (DS=3.56%). However, in day 2 the density was calculated by measuring the weight and volume, in order to get more accurate data. The polymer concentration for both days' experiments were said to be 2 g/l, which was proven not to be correct (see chapter 5.1.2). In those two day's experiments, the same weights (10 kg) and time (15 min) were implemented. The results are presented in table 5-2, where volume of polymer added was calculated according to the different polymer dosage by Eq. 4-4.

Table 5-2: Results from Day 1 and Day 2

	Polymer dosage (g poly/kg sludge)	Volume of polymer solution added(ml)	DS (%)	SS (%)
Day1	5	4.45	35.61	31.71
	10	8.90	34.81	0.70
Day2	8	5.53	17.36	3.23
	10	6.91	13.91	7.10
	12	8.30	19.81	0.29

The DS results indicated that, with 50 ml of raw sludge volume, very high DS results was obtained in day 1. However, the DS results dropped dramatically with 40ml of raw sludge volume in day 2. Even under same polymer dosage condition (10 g poly/kg sludge), 32.81% was obtained in day 1 and 13.91% was obtained in day 2. In addition, as illustrated by figure 5-1, it was hard to find any trend for neither DS results nor SS results under different polymer dosage condition.

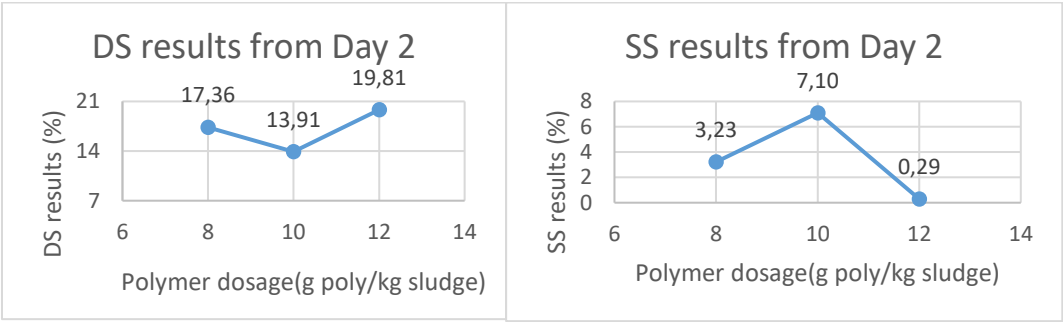


Figure 5-1: The DS and SS results of Day 2

Due to the dramatic difference between results in day 1 and day 2, and the random results variation of day 2, it was not considered as a good raw sludge volume to use. Giving concern that experiments were done in small volume (≤50ml), minor error could make remarkable difference. For example, in day 1's first experiment, 4.45ml of polymer solution was added by cylinder. It was hard to make sure all of it was added due to its stickiness. The polymer solutions remaining in the cylinder resulted in considerable errors. In order to minimise the factor, 100ml of raw sludge were used in the subsequent experiments, followed by upgrading the pressing device.

5.1.2 To decide the polymer usage

The concentration of polymer solution was a very important parameter for deciding how much polymer volume was needed for the experiment, according to Eq. 4-4. Table 5-3 reveals different stages of using polymer by different means.

Table 5-3: The four stages of using polymer agent

	Experiment day	Date	Polymer concentration (g/L)
	Day 1	26-jan	2
	Day 2	27-jan	2
	Day 3	01-feb	2.5
	Day 4	03-feb	2.5
Stage 1	Day 5	06-feb	2.1
	Day 6	08-feb	1
	Day 7	10-feb	1
Stage 2	Day 8	13-feb	1
	Day 9	17-feb	2
	Day 10	20-feb	2
	Day 11	24-feb	2
	Day 12	27-feb	2
	Day 13	03-mar	2
	Day 14	17-mar	2
Stage 3	Day 15	20-mar	2
	Day 18	10-apr	1.88
	Day 19	12-apr	2
	Day 20	19-apr	2.01
	Day 21	26-apr	2
	Day 22	27-apr	2
	Day 23	03-may	2
	Day 24	04-may	2
	Day 25	05-may	2
Stage 4	Day 26	11-may	2

In the first few experiments (stage 1), all the polymer solutions were taken from the full-scale process. According to the full scale operational parameter, the concentration was said to be 2 g/l. However, the information turned out to be unreliable. In day 3, the polymer concentration was tested by the lab and was 2.5 g/l. The same test was also done for day 5 and the result was 2.1 g/l. In table 5-3, the polymer concentration of day 1, 2 and 4 were uncertain since no lab-test was done in those days. Figure 5-2 illustrates that polymer concentration in full scale had varied a lot throughout the whole experiment period, from 1.86 g/l to 2.5 g/l (More date see appendix I). The red line in figure 5-2 is the operational parameter for polymer addition in full-scale dewatering process.

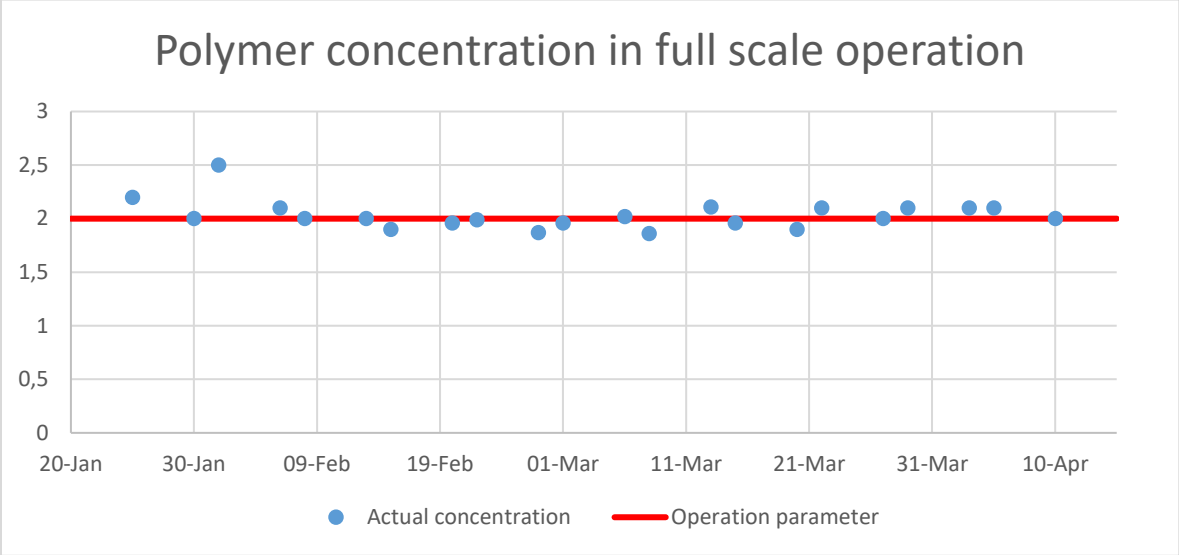


Figure 5-2: Polymer concentration of the full scale process

Since the polymer concentrations from full-scale were unstable, from stage 2 it was decided to make polymer solution with constant concentration, by diluting standard polymer agent (5 g/l) provided by polymer manufacturer. At stage 2, 1 g/l of polymer concentration was made for experiments. Table 5-4 reveals the volume of polymer added in 100ml sludge by using 1 g/l of polymer concentration, according to different polymer dosage. However, after three days' experiments, it was considered that with this concentration, large amount of external water was injected into the sludge, which means, the concentration was too diluted. For example, in day 7, with polymer dosage 13, 46.25ml of diluted polymer solution was added into 100 ml sludge. It almost equalled to half volume of the sludge liquid, which changed the water content significantly.

Table 5-4: Polymer addition of Day 6, Day 7 and Day 8

Polymer concentration (1 g/l)	Polymer dosage (g poly/kg sludge)	Volume of polymer added (ml)
Day 6	10	35.19
	11	38.71
	12	42.23
Day 7	9	32.02
	11	39.14
	13	46.25
Day 8	9	29.64
	11	36.23
	13	42.81

In order to minimize this factor, from stage 3 it was decided to use 2 g/l as polymer concentration. On the one hand, doubling the concentration reduced the amount of external water into the sludge, which gave two benefits. Firstly, it reduced the amount of reject water produced, which needs to be dealt with and represents cost if it is applied to the full-scale operation. Secondly, less water content in the sludge could result in higher DS results. On the other hand, using 2 g/l of polymer concentration was more closed to the full-scale situation, it simulated the actual dewatering process in full-scale.

However, the process of making polymer solution could involve errors making it hard to obtain 2g/l. For example, the concentration of standard polymer agent was said to be 5 g/l, but the real concentration were tested out by the dryer to be less than that. From stage 4, the polymer concentrations were recalculated by all the input information measured, according to Eq. 4-5. For instance, in day 18 (see table 5-3), the concentration of standard polymer agent was tested out to be 4.71 g/l, then 40.011 ml standard polymer agent was diluted by 60.205 ml distilled water, resulted in 100.216 ml of 1.88g/l polymer solution. With the actual concentration information, putting into Eq. 4-4, more precise polymer volume was calculated and added for sludge conditioning.

5.1.3 The order of products measurement

Table 5-5: Experimental conditions of Day 3

Experimental conditions	Day 3	
sludge volume	100	ml
Pressure Weight	10	kg
Time	10	min

Table 5-5 indicates the experimental conditions for day 3. In that day, two experiments were done with the same raw sludge volume, hanging weight and pressing time. Different polymer dosages were used to see the effect, see table 5-6. The wet cake weight in table 5-6 was the weight of sludge cake formed after pressing and sent before drying. The DS results shows that lower polymer dosage (10 g poly/kg sludge) gave lower DS result (14.75%), comparing to dosage 15 which gave higher DS result 16.39%. It was on the contrary to the trends found in day 14 and 15 (see chapter 5.2.2), which shown that the lower polymer dosage gave higher DS result. On the other hand, the wet cake results in table 5-6 shown thicker cake (22.82 g) was obtained with dosage 10, compared to 9.99 g cake obtained by dosage 15.

Table 5-6: The results from Day 3

	Polymer dosage (g poly/kg sludge)	wet cake (g)	DS (%)
Day 3	10	22.82	14.75
	15	9.99	16.39

The reason behind this was that after the pressing process in dosage 10's experiment, the presser cap was lifted up before the reject water was poured out from the basin. Since the vessel was a sealed space, vacuum force formed while the cap was lifted up, and the reject water underneath was consequently sucked up and immersed into the sludge cake again, which increased the sludge cake's water content as well as the cake weight. It resulted in decreased DS result for this experiment, so the DS results of dosage 10 from Day 3 were not authentic. For this reason, the order of measuring sludge cake and measuring reject water was changed. After the pressing process was done, the reject water was firstly dumped into the conical cup for measurement and then the presser cap was lifted up to take out the sludge cake for weight measurement and DS drying.

5.1.4 Some random results obtained in dosage tests

Table 5-7 indicates the DS and SS results from three days' experiments under the same sets of experimental conditions but under different polymer dosage. In these experiments, 10 kilograms of weight was used and all the sludge was pressed for 20 minutes. The range of polymer dosage was within 9-13 g poly /kg sludge. The DS results were also illustrated in figure 5-3.

Table 5-7: Experimental conditions and results from Day 6, 7, 8

Sludge Volume: 100ml; Hanging weight: 10kg; Pressing time: 20mins;				
Day 6	Polymer dosage (g poly/kg sludge)	10	11	12
	DS results	18.02	19.75	17.79
	SS results	5.61	14.00	2.38
Day 7	Polymer dosage (g poly/kg sludge)	9	11	13
	DS results	17.52	11.95	17.1
	SS results	0.3	0.19	0.09
Day 8	Polymer dosage (g poly/kg sludge)	9	11	13
	DS results	18.69	17.45	20.09
	SS results	4.84	0.48	0.25

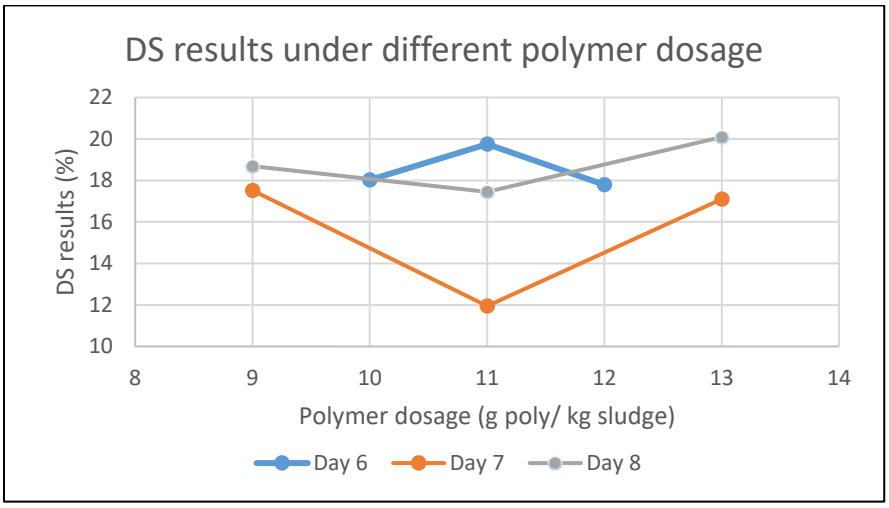
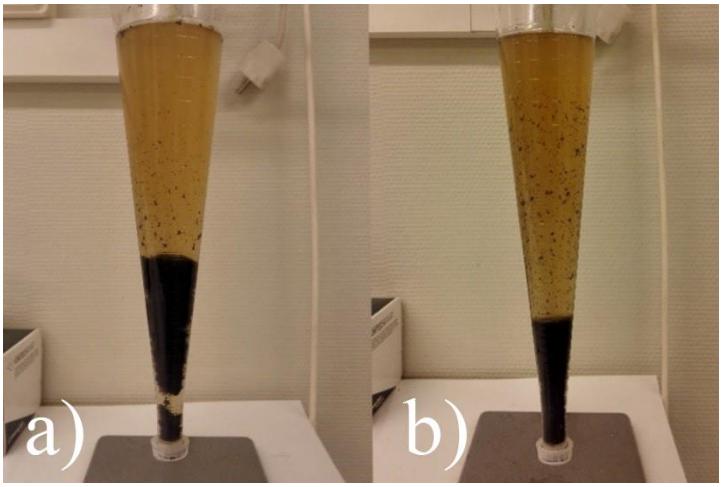
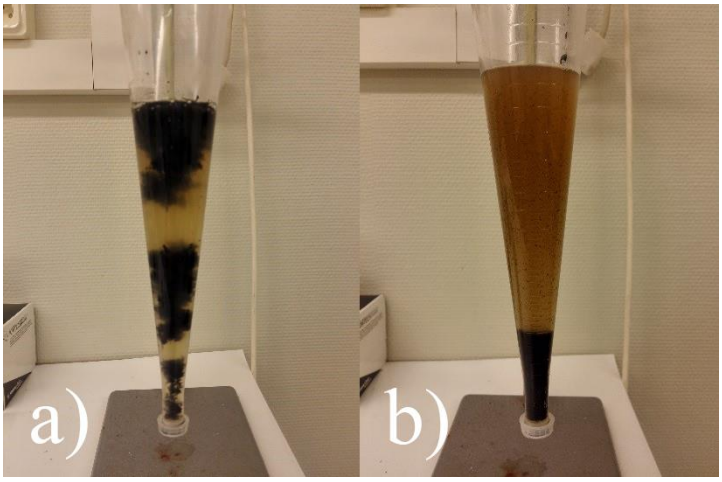


Figure 5-3: The DS results of Day 6, 7, 8

The purpose of those sets of experiments was to investigate the inherent relationship between polymer dosage and the DS results. However, the results revealed a bit random. As revealed in figure 5-3, no liner trend pattern was observed. In day 6's experiments, followed by increased polymer dosage, the DS results went up at dosage 11 and dropped afterwards. In contrast, in both day 7 and day 8's experiments, followed by increased polymer dosage, the DS results dropped first and then went up again. On the other hand, The SS results of sludge solids in the reject water were also strange. Extreme situation happened at day 6 with dosage 11. Large sludge volume in the reject water (14% of SS) was observed in the conical cup, see picture 5-1, and it was more than the sludge volume observed at lower dosage 10 (5.61% of SS). It was proven not right, since the higher polymer dosage used, the better reject water quality should be obtained (see chapter 5.2.2). Also, the sludge solids looked strange. Unlike the sludge solids in dosage 10's reject water, which mostly settled, the sludge solids in dosage 11's reject water were suspended. It is more visualized in picture 5-2, where left side shows SS result at dosage 15, which mostly suspended, and right side shows SS result at dosage 10.



Picture 5-1: SS results from Day 6 (a. Dosage 11, SS 14%; b. Dosage 10, SS 5.61%)

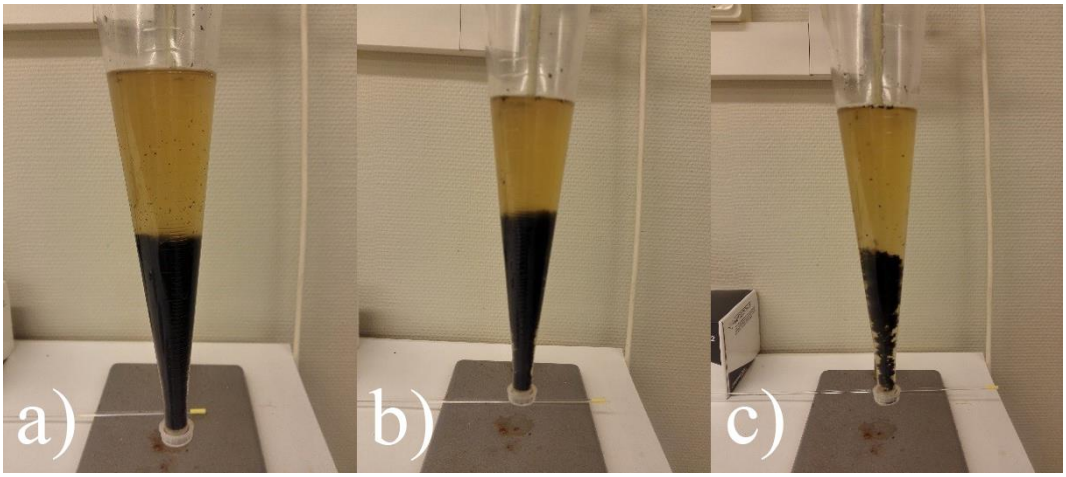


Picture 5-2: SS results from Day 4 (a.Dosage 15; b. Dosage 10)

Due to those confusing results, it was suspected that the pressing method suffered from big disturbances. In order to examine that, three experiments were done under the same experimental conditions in day 9. During that day, 10 kilograms of weight was used and dosage 11.5 were applied, and all the sludge were pressed for 20minutes. Table 5-8 indicates the DS results were still random and the calculated standard deviation for that day's DS results was 1.38, which was quite high for the same sets of experimental conditions. It is also worth to mention that day 9's experiments all got very high and abnormal SS results (see picture 5-3). Similar to the results of previous experiments (day 6, day 7 and day 8), Day 9's results did not follow any trends as well and could not be explained by different dosage usage or any other experimental condition.

Table 5-8: Experimental conditions and results of Day 9

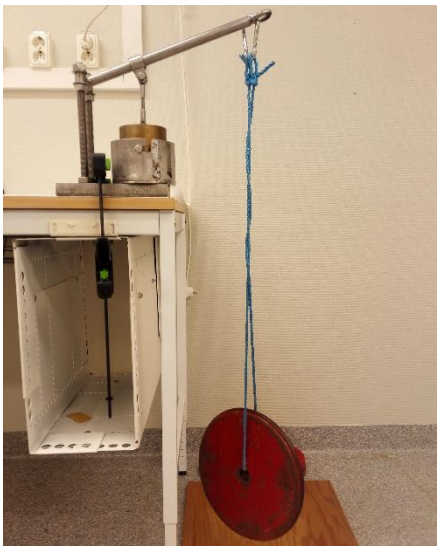
Sludge volume: 100ml; Hanging Weight: 10kg; Pressing Time: 20mins;				
Day 9	Polymer dosage (g poly/kg sludge)	11.5	11.5	11.5
	DS results (%)	21.19	18.51	19.3
	SS results (%)	28.75	31.25	20



Picture 5-3: The SS results from day 9 (a. 28.75%; b. 31.25%; c. 20%)

What caused those random DS results and high sludge volume left in the reject water? Consideration was given that cleaner reject water should be obtained with higher polymer dosage, since polymer bonded sludge particles together. But the fact was on the contrary, see pictures 5-1, 5-2 and 5-3. In addition, the abnormal sludge residual in the reject water were more like flocs, which could be the sludge complex that penetrated through the filter and entered into the reject water. It was associated with the fact that the presser cap was pushed hard and directly down to the vessel baffle and the weight was loaded instantaneously by hand, instead of using the hoister (see picture 5-4), in those experiments. At that short moment, the pressure produced was definitely higher than the one provided by regular weight (10 kilogram as used in those experiments), since the whole-body weight was used during the process. The improper operation caused uncertain DS results and large amount of sludge penetration into the reject water. Moreover, pressing and loading weight by hand had another drawback that 40 kilograms could be the maximum operating weight for a strong man and it was not good for the waist.

In the subsequent experiments, the pressing process was done more carefully and hoister was used instead of pressing the lever by hand. The effect was obvious. Since then, the DS results became good (see chapter 5.2) as well as the SS results.



Picture 5-4: Previous loading method

5.2 Presentable results for PFT method

With the foundation of proper procedure developed from the previous experiments, presentable results and perceptible trends were obtained for the PFT method. This section reveals the influence of different experimental conditions on the DS results so as to give the final configuration for the developed PFT method, and also demonstrates its feasibility.

5.2.1 To decide the hanging weight

Table 5-9: Experimental conditions of Day 11 and Day 13

	Day 11		Day 13	
Sludge volume	100	ml	100	ml
Sludge density	0.982	kg/l	0.984	kg/l
DS of raw sludge g/g	3.31	%	3.42	%
Polymer concentration	2	g/l	2	g/l
Polymer dosage	11.5	(g poly/kg sludge)	11.5	(g poly/kg sludge)
Volume of polymer added	18.7	ml	19.34	ml
Time	20	min	20	min

In order to investigate the relationship between hanging weight and the final DS result, in day 11 and day 13, several experiments were done. Table 5-9 indicates the experimental conditions for those two days. Except for the hanging weight, the rest of experimental conditions were the same that both days used polymer concentration 2 g/l (see chapter 5.1.2), polymer dosage 11.5 (see chapter 5.2.2) and pressing time 20 minutes (see chapter 5.2.3). Also, two day's experiments had similar raw sludge conditions. The slight difference between sludge densities and the DS of raw sludge led to the difference of volume polymer added, based on Eq. 4-4. The DS results of the pressed cakes, wet cake weight obtained and the SS results see table 5-10.

Table 5-10: The results from Day 11 and Day 13

Date	Hanging Weight (kg)	DS (%)	Wet cake weight (g)	SS (%)
	5	9.11	28.73	4.05
	10	18.60	10.21	18.75
	15	19.36	16.79	0.00
Day 11	20	22.03	8.88	17.65
	25	22.14	15.80	1.11
	30	24.14	13.71	0.00
	35	26.77	13.27	1.06
Day 13	40	28.49	11.91	2.11

From Table 5-10, it is clear that the DS results increased with the increasing hanging weight. When the hanging weight was 5 kilograms, it was too light to press the sludge to form a proper cake. The cake formed was thick and wet (figure 5-4, right). After 10 kilograms and so forth, the increasing trend of DS results looked liner (figure 5-4 left). It is obvious that the hanging weight had direct effect on the DS result. The DS result increased almost 10% under 40-kilogram weight comparing to 10-kilogram weight. It was calculated that 40-kilogram weight provided approximately 2.2 bar pressure on the sludge while pressing, based on Eq. 4-1, 4-2, and 4-3.

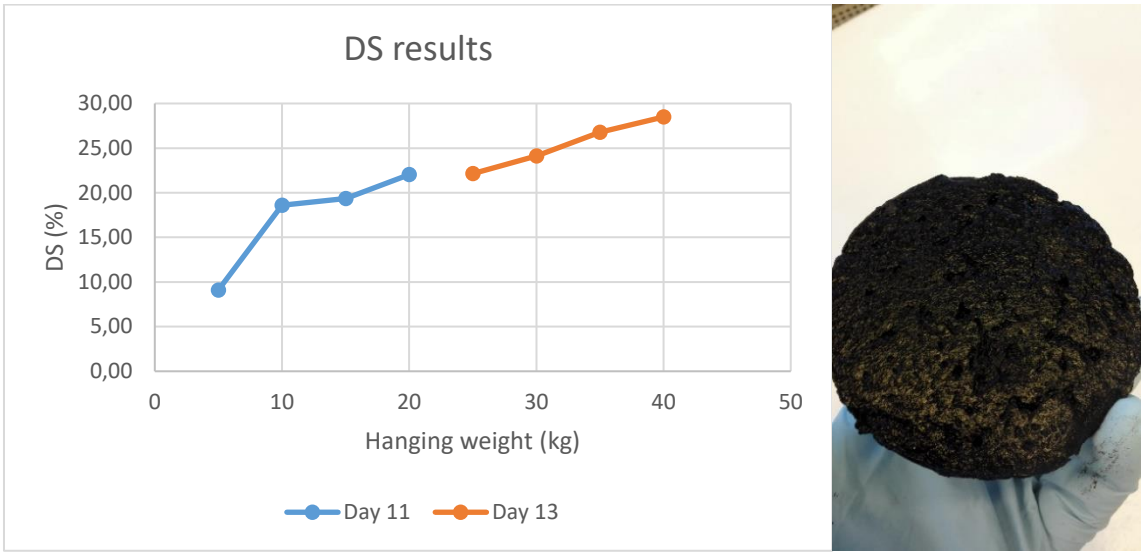


Figure 5-4: left: DS results under different weight; right: wet cake formed under 5kg

However, table 5-10 indicates that, in day 11 the wet cake obtained by the pressing device had random weight results. By comparison, the weights of wet cake obtained in day 13 had more regular trend than day 11 (see figure 5-5), that the weight of wet cake decreased with increased hanging weight. In addition, in day 11 the SS results revealed two abnormal situations that 18.75% and 17.65% of SS results were obtained under 10 kilograms and 20 kilograms of hanging weight respectively, whereas other SS results were much smaller (< 5 %). Those two abnormal SS results could be associated to the irregular curve of the wet cake weight in day 11. The reason for the unusual results was due to the pressing method (see chapter 5.1.4). In day 11, the device was pressed by hand as well as loading the weight. The process was not so smooth and the presser cap was directly pressed to the baffle, as a consequence, lots of sludge was pushed through the filter and flocculating in the reject water, causing weird wet cake weight and SS results.

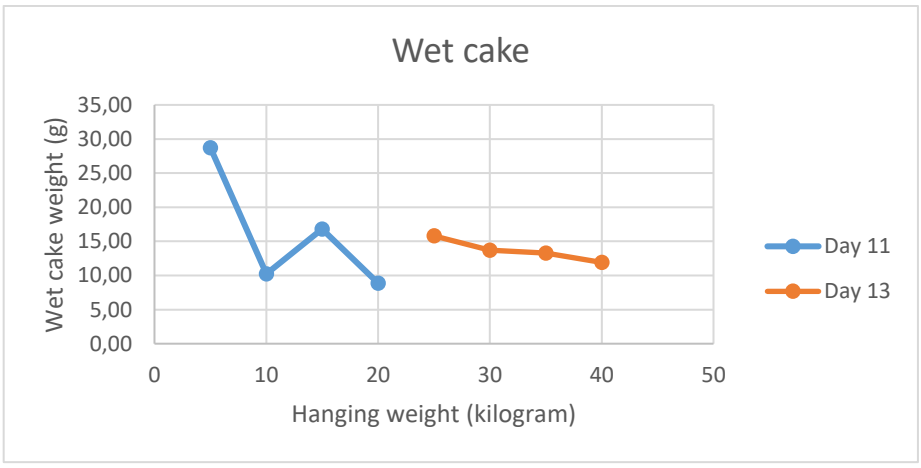


Figure 5-5: Wet cake weight obtained by different hanging weights

In the final version of the developed PFT method, 55 kilograms of hanging weight was used because it provided 3.1 bar pressure on the sludge which mimicked the pressure from full-scale sludge dewatering process.

5.2.2 To decide the polymer dosage

Table 5-11: Experimental conditions of Day 14 and Day 15

	Day 14		Day 15	
Sludge volume	100	ml	100	ml
Sludge density	0.98	kg/l	0.96	kg/l
DS of raw sludge g/g	3.65	%	3.31	%
Polymer concentration	2	g/l	2	g/l
Hanging weight	40	kilogram	40	kilogram
Pressing time	20	mins	20	mins

In order to investigate the relationship between polymer dosage and the final DS result, several experiments were done in day 14 and day 15. Table 5-11 indicates the experimental conditions for those two days. Except for the slight difference in raw sludge quality, two days' experiments share the same hanging weight (40 kilogram), polymer concentration (2 g/l) and pressing time (20 minutes). Results from table 5-12 shown that increased polymer dosage led to decreased DS results. It is also clearly revealed in figure 5-6 (left) that both day's DS trends dropped by increased polymer dosage, even though there was an overlap existed at dosage 12. The overlap was due to the distinction of two days' sludge quality. It was hard to discuss what exactly existed in the sludge every day that caused the different results. However, the identical trends of both days confirmed the effect of polymer dosage on the DS results that the higher dosage used, the lower DS results got. It is also supported by the viewpoint from previous studies that polymer reserves water inside the sludge complex and increases the difficulty of dewatering (Zhang, o.a., 2017). On the other hand, the results of wet cake weights in table 5-12 and figure 5-6 (right) also proved that with higher polymer dosage, thicker and heavier cake formed after pressing, which contained more water content inside.

Table 5-12: Results from Day 14 and Day 15

Date	Polymer dosage (g poly/kg sludge)	DS (%)	Wet cake weight (g)	SS (%)
Day 14	8	27.25	11.05	5.56
	10	25.97	12.99	1.11
	12	25.07	13.42	0.11
Day 15	12	26.58	12.62	2.15
	14	25.99	12.76	0.5
	16	25.19	13.14	0

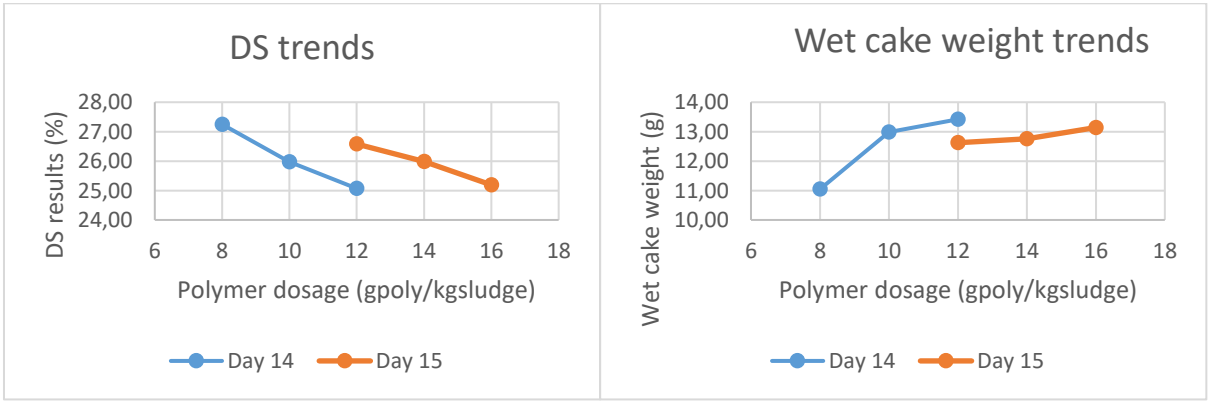
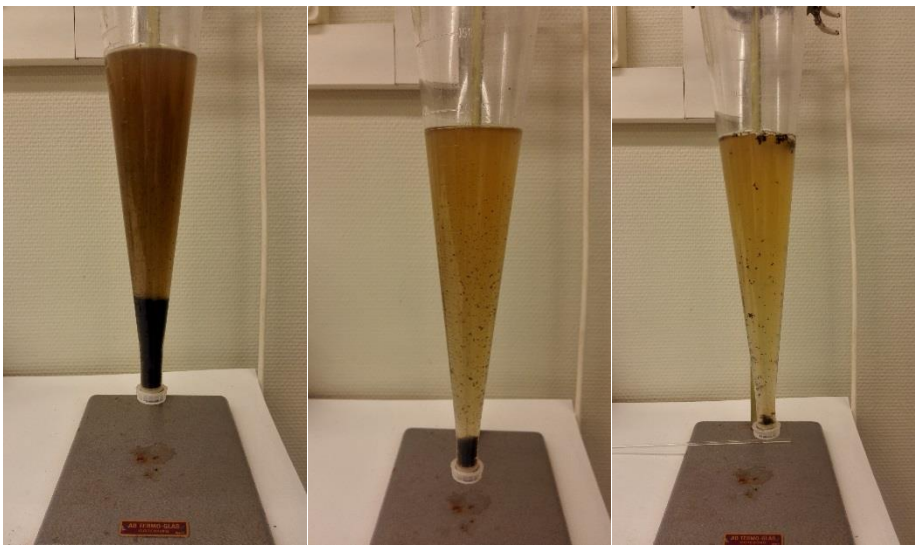


Figure 5-6 left: DS trends of Day 14 and Day 15; right: trends of wet cake weight for Day 14 and Day15

Picture 5-5 illustrates the quality of reject water obtained at day 14, it is obvious that with dosage 8 the reject water was dirty. With dosage 10 there still existed particles in the reject water. With dosage 12, the quality was clean. The few flocs were considered to be the sludge solids penetrated through the filter due to the undeveloped pressing method (hoister was not used during that stage). So, less polymer dosage resulted in bad flocculation so as the poor reject water quality. It has to be taken into consideration that bad reject water represents recycling cost.



Picture 5-5 left: dosage 8, SS 5.56%; middle: dosage 10, SS 1.11%; right: dosage 12, SS 0.11%

Through the polymer dosage experiments, it was proven that with less polymer dosage, better DS results can be obtained, however, it is under the scarification of reject water quality. Eventually, it was decided to use dosage 11.5 for the developed PFT method as a compromise of those factors. At this dosage, clean reject water was obtained and still, relatively high DS results was achieved (see chapter 5.2.5). A dosage 11.5 was also used in the current full-scale dewatering process.

5.2.3 To decide the pressing time

Table 5-13: Experimental conditions of Day 18 and Day 19

	Day 18		Day 19	
Sludge volume	100	g	100	g
DS of raw sludge g/g	3.74	%	3.58	%
Volume of polymer added	22.87	ml	20.64	ml
Polymer concentration	1.88	g/l	2	g/l
Polymer dosage	11.5	(g poly/kg sludge)	11.5	(g poly/kg sludge)
Hanging weight	40	kilogram	40	kilogram

In order to investigate the relation between pressing time and the final DS result, several experiments were done in day 18 and day 19. Table 5-13 indicates the experimental condition for those two days. Both days used 100g raw sludge for experiments instead of measuring sludge's volume and density, which made the procedure simpler and minimized the operating error. Eq. 4-4 was accordingly modified to get the right polymer volume to add. The slight difference in raw sludge condition (DS of raw sludge) gave in different polymer volume added. The polymer concentrations were recalculated by the actual input value when the polymer solution were made, instead of saying 2g/l (see chapter 5.1.2, stage 4). Both days used 11.5 g poly/kg sludge as polymer dosage and 40 kilograms as hanging weight. Table 5-14 gives the results obtained by different pressing time. The results of wet cake weights indicated that

the longer time sludge was pressed, the lighter sludge cake was formed. It is also illustrated in figure 5-7 (left), where the decreasing trends were obvious. The DS results in table 5-14 proved the idea that the longer time the sludge was pressed, the better DS result was obtained, revealing that less water content was held in the sludge cake after long time pressing. The trends of the increasing DS results were also clear in figure 5-7 (right). However, both trends in figure 5-7 were not liner, which meant after a certain time, the effect of pressing time on DS results was diminished. For instance, DS result under 20 minutes pressing time was 3.45% higher than 10 minutes pressing time, in comparison, 50 minutes' DS result was only 1.3% higher than 40 minute's result. Lastly, the SS results indicated that clear reject water were collected for all the experiments. It was attributed to the developed pressing method (by then the hoister was used).

Table 5-14: The results from Day 18 and Day 19

Date	Pressing time (mins)	Wet cake weight (g)	DS (%)	SS (%)
Day 18	10	16.56	21.02	0
	20	13.91	24.47	0.5
	30	12.94	27.19	0.1
Day 19	30	13.26	27.21	0.5
	40	12.06	28.97	0
	50	11.75	30.27	0

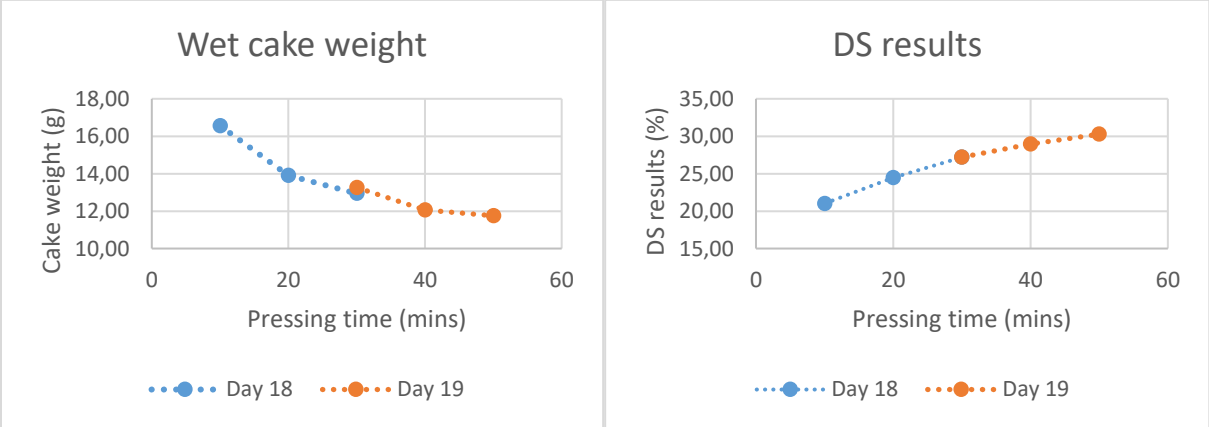


Figure 5-7 left: Trends of wet cake weight of Day 18 and Day 19; right: DS trends of Day 18 and Day 19

Through the pressing time experiments, it was proven that with longer pressing time, better DS results can be obtained. However, the increase of DS result was not infinite, the effect faint after 40 minutes pressing time. Eventually, it was decided to use 30 minutes as the experimental condition for the developed PFT method. Considering the dryer took around 30 minutes to finish its job and be ready for the next sample, this time-frame makes experiment more efficient.

5.2.4 To decide polymer types

Table 5-15: Experimental conditions of Day 21 and Day 22

	Day 21		Day 22	
Sludge volume	100	g	100	g
DS of raw sludge	3.40	%	3.46	%
Polymer concentration	2	g/l	2	g/l
Polymer dosage	11.5	(g poly/kg sludge)	11.5	(g poly/kg sludge)
Volume of polymer added	19.53	ml	19.88	ml
Hanging weight	55	kilogram	55	kilogram
Pressing time	40	mins	30	mins

With the proved relationship between polymer dosage, pressing time, hanging weight and the final DS results, this method was relatively developed. Based on the obtained experimental conditions, this PFT method was used to test out the effect of four different polymer types on DS result. Z7557, Z7587, Z8160 and Z8180 were the four different polymer types provided by their manufacturer BASF. Table 5-15 indicates that experiments were based on two samples. Due to the raw sludge difference, the added polymer volume was calculated respectively. Two-time frame (40 minutes and 30 minutes) was used to give the results in different view-points. Table 5-16 indicates the DS results and SS results. It is obvious that for both days' experiments, the SS results were low, sludge solids were rarely observed in the reject water. The DS results was interpreted into figure 5-8, it is clear that two days' results followed the same pattern, despite of different pressing time. It is reasonable that day 22's results were generally lower than Day 21's, since the pressing time of day 22 was 10 minutes less than day 21's. Both days' best result pointed to polymer type Z7587, which reached DS result of 31.46% for day 21 and 30.1% for day 22. Polymer type Z8180, the one used in previous experiments developing the method, had the second-best results. However, the difference in DS results by different polymer types were not so significant. In full-scale operation, the slight improvement could make a difference.

Table 5-16: The results from Day 21 and Day 22

Date	Polymer types	DS %	SS %
Day 21	Z7557	29.89	0.3
	Z7587	31.46	0
	Z8160	29.50	0
	Z8180	31.06	0
Day 22	Z7557	29.30	0
	Z7587	30.10	0
	Z8160	28.99	0
	Z8180	29.98	0

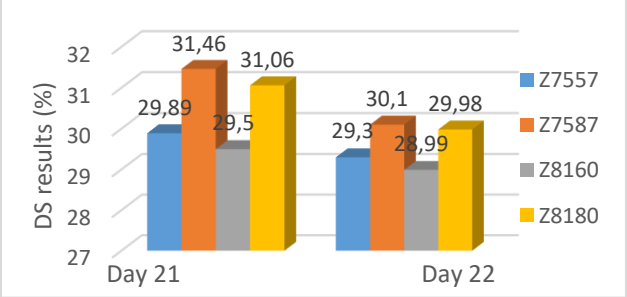


Figure 5-8: The DS results of different polymer types

Through these two sets of experiments, polymer type Z7587 was recommended.

5.2.5 Standard deviation of the developed PFT method

In this section, nine repetitive experiments were done in order to get the standard deviation for the decided experiment configuration, see table 5-17. This set of experiments were done within 3 days. One large sample was taken from the site and stored in the refrigerator for three experiment days' usage. Thus, nine experiments were done using exactly the same raw sludge sample and the same experimental conditions which were recommended from previous sections.

Table 5-17: Experimental conditions of repetitive experiments

Sludge volume	100	g
DS of raw sludge g/g	3.35	%
Polymer type	Z7587	
Polymer concentration	2.00	g/l
Polymer dosage	11.5	(g poly/kg sludge)
Volume of polymer added	19.26	ml
Hanging weight	55	kg
Pressing time	30	mins

Table 5-18 indicates the DS results of nine experiments, which revealed that the average result by the developed method was 30.18%, above 30%. The standard deviation of the results was less than 0.3, proved the reliability and repeatability of the method. It is also worth to mention that the SS results of the nine experiments were approximately 0% (see raw data in appendix III), proved that clean reject water can be obtained by this developed method.

Table 5-18: The DS results of repetitive experiments

Date	Experiment Number	DS %
	1	30.25
	2	30.43
Day 23	3	30.15
	4	29.71
	5	30.02
Day 24	6	30.20
	7	30.75
	8	29.80
Day 25	9	30.29
Average		30.18
Standard deviation		0.297
Coefficient of variation		1%

5.3 Others

5.3.1 CST tests

The CST experiments were all conducted with mesophilic sludge. As mentioned in the introduction part of chapter 4 **Methodology**, the CST experiments were done at three point in coordination with the development of PFT method.

At the first point, when the raw sludge liquid was filled in the metal vessel, it was observed that the water content in raw sludge was hardly sucked out by the suction paper. Nine CTS tests were done with the same raw sludge sample. Table 5-19 indicates that the CST results varied a lot, from 443.1 seconds to 544.4 seconds. The standard deviation of the results was 28.08, announced low reliability of this method for testing dewater-ability of raw sludge liquid. However, the results shown that in general it took long time (more than 7 minutes) for water to pass the small distance between the two electronic rings. This phenomenon suggested that water content was closely bonded within the raw sludge. In another word, raw sludge liquid has low dewatering effect, in order to separate the water, polymer must be added.

Table 5-19: CST results for raw sludge liquid

Experiment No.	1	2	3	4	5
CST (s)	518.7	466.8	544.4	443.1	491.9
6	7	8	9	Standard deviation	Coefficient of variation
519.5	500.4	493.4	499.2	28.08	5.65%

Table 5-20 indicates the CST results of sludge complex (the mixture of sludge and polymer), which was the second point when the polymer (dosage 11.5) was added but before the pressing process. Three sludge complex sample were made for the tests, by the same raw sludge and polymer adding condition. Each sample was divided into four equal portion to fill into the metal vessel for testing. Results indicated that, even though the experimental conditions were the same, there was no coincidence or trend between the results. Sometimes it took short time, say 11.4 seconds (the first result of the first sample in table 5-20), to finish the test, which suggested that the sludge complex contained a lot of dissociated water. Sometimes it took extremely long, say 132 seconds (the first result of the third sample in table 5-20), which indicated that the sample was hard for dewatering. In reality, it was difficult to keep the sludge complexes in steady and similar conditions (CV = 107%). Since the sample was a complex (see picture 5-6), some of them contained more water and another contained less, even though they were all from the same raw sludge sample and filtered in the same amount of time. More CST results regarding different polymer dosage adding can be found in appendix III, which also varied and had no trend to follow. Then, the filtered water from the sludge complex were also tested by CST method, see chapter 4.3 **Experiment procedures** of CST test. This time, the water spread swift, it took only 0.7s to finish the test, which was the minimum digital number that the device could reveal. It provided limited information for comparison, so using CST method to test the filtered water was impractical.

Table 5-20: Experimental conditions and the CST results for the second point

Experimental conditions				
Sludge volume	50	ml		
Sludge density	0.97	kg/l		
DS of raw sludge g/g	3.75	%		
Polymer concentration	2	g/l		
Polymer dosage	11.5	(g poly/kg sludge)		
Volume of polymer added	10.51	ml		
CST results (s)				
First sample	11.4	13.1	13.1	19.9
Second sample	23.3	23.9	13.5	26.7
third sample	132	37.1	23.4	14.9
Mean	30.76			
Standard deviation	32.86			
Coefficient of variation	107%			

Picture 5-6: Sludge complex for CST tests

At the last point, the CST method was used to test sludge cake's dewatering characteristic. It was observed that water was rarely sucked out from the pressed cake by the suction paper, so the test could not be finished. The fact was, the sludge cake contained very limited water after the pressing process to implement the CST method.

5.3.2 Thermophilic sludge

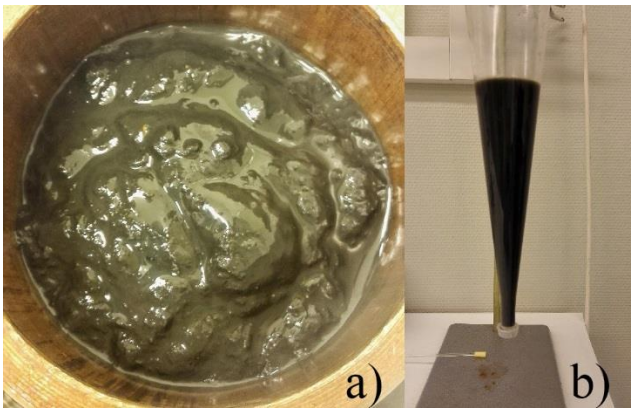
Table 5-21: Experiment for comparing the mesophilic and thermophilic sludge

Experimental condition	Day 16	
Raw sludge volume	100	g
Polymer concentration	2	g/l
Polymer dosage	11.5	(g poly/kg sludge)
Hanging weight	40	kg
Pressing time	20	mins
DS of raw mesophilic sludge	3.57	%
DS of raw thermophilic sludge	4.67	%

Results			
Sludge type	Volume of polymer added (ml)	DS %	SS %
Mesophilic	20.55	25.17	0.3
Thermophilic	26.87	32.28	undetected

One experiment was done to compare the dewater-ability of thermophilic sludge (TS) with mesophilic sludge (MS). The experimental condition and results was indicated in table 5-21. The experimental condition was not the final version, since it was done in the middle period. Here only describe what was observed during the experiment and the DS result could only be taken as a reference. Both sludge sample were taken from the pilot reactors. The thermophilic reactor increased the temperature from mesophilic condition dramatically and kept in stable operation in three weeks. In the beginning of the conversion, **unacceptable odour** was experienced. It is said that the increased odour was due to the short-term temperature increases as a result of accumulation of VFA (Iranpour, o.a., 2005). After three weeks of operation, the situation became better, but the smell was still detectable and was complained by other lab staff. It explained why only one experiment was done to compare the thermophilic and mesophilic sludge throughout the whole study.

From table 5-21, it is obvious that raw TS had higher DS (4.67%), comparing with raw MS (3.57%). Also, the raw TS liquid looked thicker than MS liquid. After mixing with polymer, the flocculated TS complex looked more homogeneous and viscous, where large amount of water seemed still bound in between, see picture 5-7-a. By comparison, the water content and sludge complex of MS was more separated, see figure 4-10-b in chapter 4.2.2. The reject water of TS revealed totally dark and dirty (picture 5-7-b), so the SS result could not be determined. The poor sludge settling in reject water has been linked to the temperature variations, which causes high effluent suspended solids, effluent turbidity and biomass washout (Gao, Leung, Qin, & Liao, 2011). However, the TS revealed a better dewater-ability during this experiment. 32.28% of DS result was obtained for TS, comparing to 25.17% for MS.



Picture 5-7 a) Thermophilic sludge complex formed after adding polymer; b) Reject water from thermophilic sludge

5.3.3 Blank experiment

One blank experiment was done for raw sludge test by PFT method. During the experiment, no polymer was added and the raw sludge was placed on a normal coffee filter setting on the baffle and pressed. The pressing process was hard to be implemented under 40 kilograms hanging weight and few liquids penetrated through the filter was still in raw sludge form. It complied with the announcement from previous study that the jelly-like layer formation of the inner microorganisms attracts the water strongly (Gillberg, Hansen, Karlsson, Enkel, & Pålson, 2003). So, it is not suitable to use PFT method to make the direct comparison between raw sludge. Polymer conditioning is necessary.

6 Conclusion

This study has developed a PFT method for sludge dewater-ability tests and provided the right procedure to implement it (see chapter 4.3). This developed method is based on the pilot-scale experiment but the results can provide guidance for full-scale dewatering operation on aspects such as polymer type, pressure adjustments and so on.

It was shown that using larger raw sludge volume (100ml) resulted in more reliable results than small sludge volume (<50ml). Also, it is suggested to make polymer solution from standard agent in order to get a constant quality, instead of taking the polymer from the full-scale process where the polymer concentration varies. The way of making polymer solution and the storage is given in chapter 4.2.2. Regarding operation, the pressing process should be done slowly and smoothly to obtain good DS results and clear reject water. After the pressing process, the reject water should be poured out first then the presser cap can be lifted up to take out the sludge, to prevent the vacuum force withdrawing the reject water.

Based on the refined experimental procedure, the influence of different experimental conditions on the final DS result was investigated. Through the hanging weight experiments, it proved that the heavier weight used, the higher DS result obtained. It is also shown that, with proper pressing method, clean reject water can be obtained under large pressure (3.1 bar) and polymer dosage 11.5 g/kg. Through the polymer dosage experiments, it was proven that with less polymer dosage, the PFT method have better DS result, however, it was under the scarification of clean reject water. In order to have the best effect, compromise should be made with the dosage of polymer used. Through the pressing time experiments, it was proven that with longer pressing time, better DS results can be obtained. However, the increase of DS result was not infinite, the effect diminished after a certain pressing time (40 minutes). The reject water quality, to conclude, is mainly decided by the pressing method and polymer dosage, and less affected by pressing time and hanging weight (< 55 kg). Then, different polymer types were tested and found that Z7587 had the best effect. Lastly, repetitive experiments were done to get the standard deviation (0.297) and coefficient of variation (1%), and this showed the feasibility and reliability of the developed PFT method. The recommended experiment configuration is listed in table 6-1.

Table 6-1: The recommended experiment configuration

Sludge volume	100	g
Polymer type	Z7587	
Polymer concentration	2.00	g/l
Polymer dosage	11.5	(g poly/kg sludge)
Hanging weight	55	kg
Pressing time	30 or 40	mins

For CST method, it was proved to be impractical for raw sludge test, since it was hard to suck water out of sludge without mixing with polymer, although raw sludge was in liquid form. Also, the CST method

was not applicable for testing sludge complex, since it was hard to control complex's condition. Lastly, the CST method could not give any result for sludge cake test since too limited water was sucked to finish the test. So, the CST method was abandoned in the end.

One comparison experiment was done for thermophilic sludge and mesophilic sludge, however, due to the odour problem, limited result was obtained. Further study could be done using this developed PFT method after the thermophilic reactor become more stable. Another master student, Tineke Bittlingmayer, is taking care of the second stage of comparison study in Gryaab AB at the time of writing.

7 Recommendation and suggestion for further study

Due to time frame and lab conditions, several issues stay unexplored. Further researches can be done regarding following aspects.

Potential improvements on DS result:

- The weight limit (> 55 kg) can be explored to reveal the effect on DS result.
- Higher polymer concentration (2 g/l) can be used to minimise the water injection. However, previous study has mentioned that high concentration of polymer could increase the bulk turbulence in the fluid in full-scale operation (Crawford, Mordant, Xu, & Bodenschatz, 2008).
- It was said by the polymer supplier that, the optimal mixing times of polymer and sludge could be investigated (12 times of mixing was implemented in this study), since on the one hand, the sludge complex should be well-mixed; on the other hand, it could break down the sludge complex's structure and make them scattered again by exceeding a certain mixing times.
- As mentioned in chapter 5.2.2, polymer has strong water-reserving ability which impede obtaining high DS result, subsequent chemical treatment could be implemented to release the water held in the sludge complex. For example, Na_2SiO_3 was used in previous study for deep dewatering of the urban sewage sludge (Zhang, o.a., 2017).

Regarding the equipment:

- In this study, samples were taken from on-site and stored in room temperature, which was in different condition from the real operation (mesophilic or thermophilic conditions). It is recommended to use thermostatic container to keep the samples in constant environment.
- Since most WWPTs have air pressure line (> 3 bar), it is recommended to upgrade the pressing device by using air force with controllable pressing speed and pressure meter. It can also investigate the effect of descending ratio (30sec/5cm, 1min/5cm, 2min/5cm etc.) on the DS result and the reject water's cleanness.

Thermophilic sludge experiment:

- Although the experiment of thermophilic sludge has been stopped due to odour problem. The smell situation became better after several weeks' operation. It could be the reason that microbial community in the system became stable and adapted. Previous study (Schafer & Farrell , 2002) has suggested that the thermophilic sludge can also be dewatered after 1 or 2 days' low temperatures (35–43°C) storage to avoid the odour emissions.

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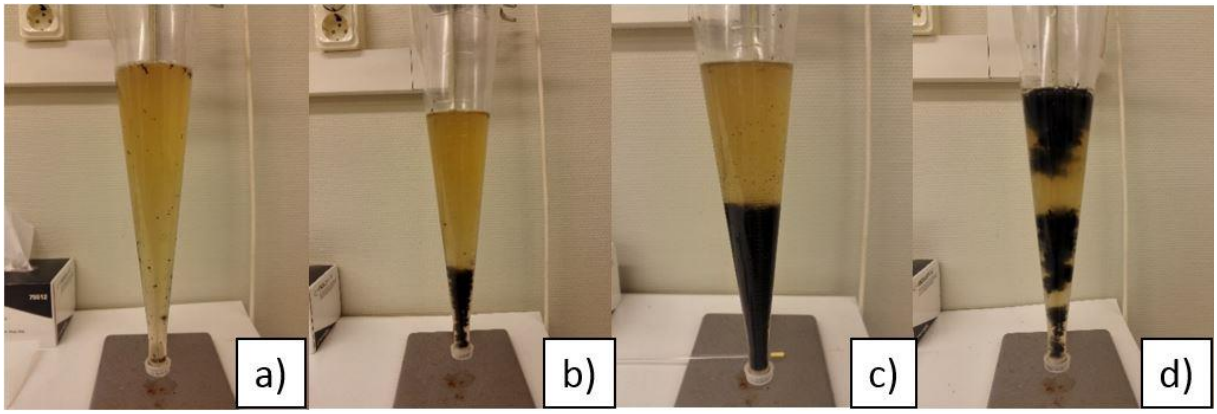
Appendix I

Polymer concentration from full scale

Time	TS poly(g/L)
2017-01-02 07:25	2
2017-01-04 07:13	2
2017-01-11 07:24	2.2
2017-01-16 07:11	2.1
2017-01-18 07:18	2.2
2017-01-23 07:26	2.2
2017-01-25 07:08	2.2
2017-01-30 07:56	2
2017-02-01 07:53	2.5
2017-02-06 08:00	2.1
2017-02-08 08:12	2
2017-02-13 08:15	2
2017-02-15 08:15	1.9
2017-02-20 07:01	1.96
2017-02-22 07:07	1.99
2017-02-27 07:02	1.87
2017-03-01 07:00	1.96
2017-03-06 08:04	2.02
2017-03-08 07:54	1.86
2017-03-13 08:00	2.11
2017-03-15 06:55	1.96
2017-03-20 06:54	1.9
2017-03-22 06:36	2.1
2017-03-27 06:59	2
2017-03-29 06:57	2.1
2017-04-03 07:14	2.1
2017-04-05 07:04	2.1
2017-04-10 07:23	2

Appendix II

Pictures of the reject water

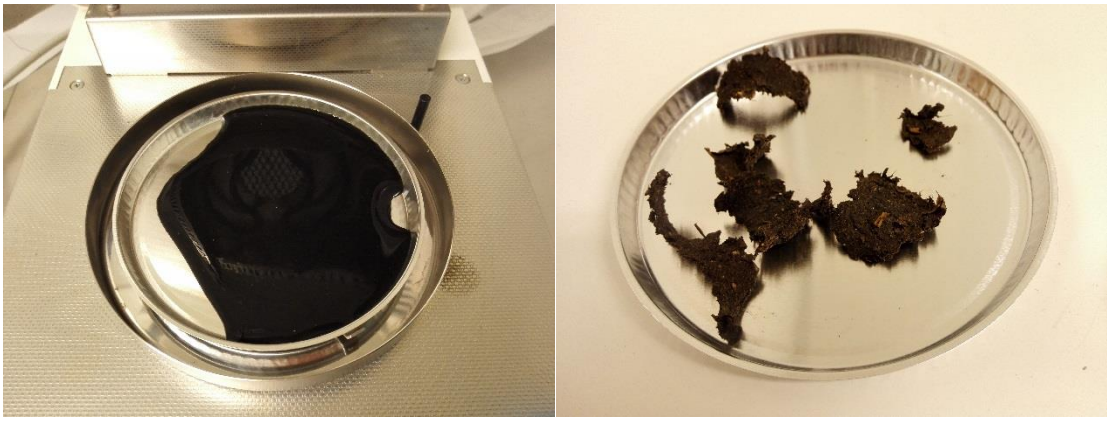


Description:

a) Clean reject water, SS <1%; b) Relatively clean, SS 1 %< x<10%;

c) Dirty reject water, SS >10%; d) Failed result

Pictures of the raw mesophilic sludge before (left) and after (right) drying



Pictures of the sludge cake and the reject water obtained under the recommended method

Appendix III

Raw experimental data

2017-01-26, Day 1

Experimental conditions		
sludge volume	50	ml
DS sludge g/g	3.56	%
polymer concentration	2	g/l
Pressure Weight	10	kg
Time	15	min

Results						
polymer dosage (gpoly/kgsludge)	Volume polymer/ml	dry cake /g	wet cake /g	DS %	rejected water/ ml	sludge settlement/ml
5	4.45	3.611	10.139	35.61	13	41
10	8.9	4.109	11.794	34.81	0.3	43

2017-01-27, Day 2

Experimental conditions		
sludge volume	40	ml
sludge density	0.96	kg/l
DS sludge g/g	3.6	%
polymer concentration	2	g/l
Pressure Weight	10	kg
Time	15	min

Results						
polymer dosage (gpoly/kgsludge)	Volume polymer/ml	dry cake /g	wet cake /g	DS %	rejected water/ ml	sludge settlement /ml
8	5.53	1.119	6.447	17.36	1	31
10	6.91	0.919	6.608	13.91	2.2	31
12	8.30	1.32	6.664	19.81	0.1	34

2017-02-01, Day 3

Experimental conditions		
sludge volume	100	ml
sludge density	0.98	kg/l
DS sludge g/g	3.8	%
polymer concentration	2.5	g/l
Pressure Weight	10	kg
Time	10	min

Results						
polymer dosage (gpoly/kgsludge)	Volume polymer/ml	dry cake /g	wet cake /g	DS %	sludge settlement/ml	Filtered water/ ml
10	14.9	3.367	22.821	14.75	2	90
15	22.35	1.639	9.997	16.39	0	95

2017-02-03, Day 4

Experimental conditions		
sludge volume	100	ml
sludge density	0.96	kg/l
DS sludge g/g	3.75	%
polymer concentration	2.5	g/l
Pressure Weight	10	kg
Time	10	min

Results								
polymer dosage (gpoly/kgsludge)	Volume polymer/ml	dry cake /g	wet cake /g	DS %	sludge settlement/ml	Filtered water/ ml	SS %	CST /s
10	14.44	10.41	1.65	15.85	3.8	78	4.87	42.4
12.5	18.05	10.28	1.49	14.45	1.4	81	1.73	27.7
15	21.66	9.56	1.61	16.8	false	83	false	36.1

2017-02-06, Day 5

Experimental conditions		
sludge volume	100	ml
sludge density	0.99	kg/l
DS sludge g/g	3.59	%
polymer concentration	2.1	g/l
Pressure Weight	10	kg
Time	20	min

Results								
polymer dosage (gpoly/kgsludge)	Volume polymer/ml	dry cake /g	wet cake /g	DS %	sludge settlement/ml	Filtered water/ ml	SS %	CST /s
10	16.88	1.86	10.17	18.26	12	91	13.19	29.3
12.5	21.10	1.60	10.04	15.88	0.1	89	0.11	51.6
15	25.32	1.49	10.03	14.85	0	90	0.00	71.9

2017-02-08, Day 6

Experimental conditions		
sludge volume	100	ml
sludge density	0.94	kg/l
DS sludge g/g	3.76	%
polymer concentration	1	g/l
Pressure Weight	10	kg
Time	20	min

Results

polymer dosage (gpoly/kgsludge)	Volume polymer/ml	dry cake /g	wet cake /g	DS %	sludge settlement/ml	Filtered water/ ml	SS %	CST /s
10	35.19	1.78	9.89	18.02	5.5	98	5.61	98.6
11	38.71	1.83	9.28	19.75	14	100	14.00	108.8
12	42.23	1.93	10.82	17.79	2.5	105	2.38	112.9

2017-02-10, Day 7

Experimental conditions		
sludge volume	100	ml
sludge density	0.97	kg/l
DS sludge g/g	3.65	%
polymer concentration	1	g/l
Pressure Weight	10	kg
Time	20	min

Results								
polymer dosage (gpoly/kgsludge)	Volume polymer/ml	dry cake /g	wet cake /g	DS %	sludge settlement/ml	Filtered water/ ml	SS %	CST /s
9	32.02	2.03	11.56	17.52	0.3	100	0.3000	70.1
11	39.14	1.29	10.76	11.95	0.2	107	0.1869	158.5
13	46.25	1.87	10.95	17.10	0.1	115	0.0870	159.1

2017-02-13, Day 8

Experimental conditions		
sludge volume	100	ml
sludge density	0.98	kg/l
DS sludge g/g	3.35	%
polymer concentration	1	g/l
Pressure Weight	10	kg
Time	20	min

Results									
polymer dosage (gpoly/kgsludge)	Volume polymer/ml	dry cake /g	wet cake /g	DS %	Wet cake /g	sludge settlement /ml	Filtered water/ ml	SS %	CST /s
9	29.64	1.92	10.28	18.69	14	4.5	93	4.83	29.3
11	36.23	1.86	10.65	17.45	15.569	0.5	105	0.47	85
13	42.81	1.85	10.37	17.80	16.237	0.1	120	0.08	57.7
13*	42.81	2.07	10.29	20.09	14.308	0.3	120	0.25	75.9

2017-02-17, Day 9

Experimental conditions		
sludge volume	100	ml
sludge density	0.96	kg/l
DS sludge g/g	3.75	%
polymer concentration	2	g/l
Pressure Weight	10	kg
Time	20	min

Results						
(gpoly/kgsludge)	Volume polymer/ml	Wet cake weight /g	DS %	sludge settlement/ml	Filtered water/ ml	SS %
11.5	20.69	11.67	21.19	23	80	28.7500
11.5	20.69	9.44	18.51	25	80	31.2500
11.5	20.69	15.50	19.30	18	90	20.0000

2017-02-20, Day 10

Experimental conditions		
sludge volume	100	ml
sludge density	0.97	kg/l
DS sludge g/g	3.75	%
polymer concentration	2	g/l
Pressure Weight	10	kg

Results								
Time	polymer dosage (gpoly/kgsludge)	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge solid /ml	Filtered water/ ml	SS %
30	11.5	21.02	21.05	13.91	20.92	7.5	85	8.8235
20	11.5	21.02	21.04	17.69	19.04	1	90	1.1111
10	11.5	21.02	21.06	10.80	20.47	3	85	3.5294

CST tests, sludge volume: 50 ml						
polymer dosage (gpoly/kgsludge)	Volume polymer needed/ml	Volume polymer added/ml	CST /s			
11.5	10.51	10.52	11.4	13.1	13.1	19.9
11.5	10.51	10.5	23.3	23.9	13.5	26.7
11.5	10.51	10.56	132	37.1	23.4	14.9

2017-02-24, Day 11

Experimental conditions		
sludge volume	100	ml
sludge density	0.9824	kg/l
DS sludge g/g	3.31	%
polymer concentration	2	g/l
Time	20	min

Results								
Weight	polymer dosage (gpoly/kgsludge)	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	Sludge solids /ml	Filtered water/ ml	SS %
5	11.5	18.70	18.77	28.73	9.11	3	74	4.05
10	11.5	18.70	18.7	10.21	18.60	15	80	18.75
15	11.5	18.70	18.71	16.79	19.36	0	85	0
20	11.5	18.70	18.71	8.876	22.03	15	85	17.64

2017-02-27, Day 12

Experimental conditions		
sludge volume	100	ml
sludge density	0.98	kg/l
DS sludge g/g	3.46	%
polymer concentration	2	g/l
Time	20	min

Results								
Weight	polymer dosage (gpoly/kgsludge)	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	Sludge solids /ml	Filtered water/ ml	SS %
20	11.5	19.47	19.471	14.14	22.38	0.5	90	0.56
20	11.5	19.47	19.47	13.82	23.12	3	90	3.33
20	11.5	19.47	19.52	15.74	19.98	0	90	0.00

2017-03-03, Day 13

Experimental conditions		
sludge volume	100	ml
sludge density	0.9836	kg/l
DS sludge g/g	3.42	%
polymer concentration	2	g/l
time	20	min

Results								
Weight/kg	polymer dosage (gpoly/kgsludge)	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water / ml	SS %
25	11.5	19.34	19.36	15.80	22.14	1	90	1.11
30	11.5	19.34	19.36	13.71	24.14	0	93	0.00
35	11.5	19.34	19.36	13.27	26.77	1	94	1.06
40	11.5	19.34	19.38	11.91	28.49	2	95	2.11

2017-03-17, Day 14

Experimental conditions		
sludge volume	100	ml
sludge density	0.98	kg/l
DS sludge g/g	3.65	%
polymer concentration	2	g/l

Results								
Time/min	Weight/kg	polymer dosage (gpoly/kgsludge)	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water/ ml	SS %
20	40	8	14.271	11.05	27.25	5	90	5.55
20	40	10	17.81	12.99	25.97	1	90	1.11
20	40	12	21.39	13.42	25.07	0.1	90	0.11

2017-03-20, Day 15

Experimental conditions		
sludge volume	100	ml
sludge density	0.96	kg/l
DS sludge g/g	3.31	%
polymer concentration	2	g/l

Results								
Time/min	Weight/kg	polymer dosage (gpoly/kgsludge)	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water/ ml	SS %
20	40	12	19.18	12.62	26.58	2	93	2.15
20	40	14	22.31	12.76	25.99	0.5	100	0.50
20	40	16	25.5	13.14	25.19	0	103	0.00

2017-03-27, Day 16

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
polymer concentration	2	g/l
polymer dosage	11.5	(gpoly/kgsludge)
Weight	40	kg
Time	20	mins

Results							
Sludge type	Ds of raw sludge % (g/g)	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement/ml	Filtered water/ ml	SS %
Mesophilic	3.57	20.55	14.07	25.17	0.3	100	0.3000
Thermophilic	4.67	26.87	12.27	24.67	?? (<1)	120	<0,8

2017-03-29, Day 17

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
polymer concentration	2	g/l
Ds of raw sludge % (g/g)	4.49	g/g
Weight	40	kg
Time	20	mins

Results							
Sludge type	polymer dosage	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	Filtered water/ ml	SS %
Thermophilic	11.5	25.82	25.9	11.25	32.28	120	***

2017-04-10, Day 18

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
DS sludge g/g	3.74	%
polymer concentration	1.88	g/l
Weight	40	kg

Results								
polymer dosage(gpoly/kgsludge)	Time	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water/ ml	SS %
11.5	10	22.87	22 871	*	21.02	0	102	0.00
11.5	20	22.87	22 886	*	24.47	0.5	100	0.50
11.5	30	22.87	22 880	*	27.19	0.1	110	0.09

2017-04-12, Day 19

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
DS sludge g/g	3.58	%
polymer concentration	2.00	g/l
Weight	40	kg/l

Results								
polymer dosage (gpoly/kgsludge)	Time	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water /ml	SS %
11.5	30	20.59	20.64	13.26	27.21	0.5	107	0.46
11.5	40	20.59	20.64	12.06	28.97	0	115	0.00
11.5	50	20.59	20.63	11.75	30.27	0	115	0.00

2017-04-19, Day 20

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
DS sludge g/g	6.06	%
polymer concentration	2.01	g/l
Weight	55	kg
Time	30	min

Results						
polymer dosage (gpoly/kgsludge)	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement/ml	Filtered water/ ml	SS %
11.5	34.73	19.38	31.08	0	115	0.00

2017-04-26, Day 21

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
DS sludge g/g	3.4	%
polymer concentration	2.00	g/l
polymer dosage	11.5	(gpoly/kgsludge)
Weight	55	kg
Time	40	mins

Results								
polymer concentration	Polymer type	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water/ ml	SS %
2.00	Z7557	19.53	19.56	11.39	29.89	0.3	100	0.30
2.00	Z7587	19.59	19.72	10.67	31.46	0	110	0.00
2.00	Z8160	19.54	19.68	11.23	29.50	0	103	0.00
2.00	Z8180	19.58	19.60	10.71	31.06	0	115	0.00

2017-04-27, Day 22

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
DS sludge g/g	3.46	%
polymer concentration	2.00	g/l
polymer dosage	11.5	(gpoly/kgsludge)
Weight	55	kg
Time	30	mins

Results							
Polymer type	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water/ ml	SS %
Z7557	19.88	19.91	11.29	29.30	0	102	0.00
Z7587	19.88	19.88	11.32	30.10	0	115	0.00
Z8160	19.88	19.89	11.37	28.99	0	107	0.00
Z8180	19.90	19.90	11.51	29.98	0	107	0.00

2017-05-03, Day 23

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
DS sludge g/g	3.35	%
polymer concentration	2.00	g/l
polymer dosage	11.5	(gpoly/kgsludge)
Weight	55	kg
Time	30	mins

Results								
No.	sludge volume (g)	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water /ml	SS %
1	100.040	19.26	19.30	11.35	30.25	0	100	0.00
2	100.030	19.26	19.31	11.07	30.43	0	102	0.00
3	100.037	19.26	19.31	11.33	30.15	0	103	0.00

2017-05-04, Day 24

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
DS sludge g/g	3.35	%
polymer concentration	2.00	g/l
polymer dosage	11.5	(gpoly/kgsludge)
Weight	55	kg
Time	30	mins

Results								
No.	Sludge volume added (g)	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water/ ml	SS %
4	100.053	19.26	19.30	11.28	29.71	0	102	0.00
5	100.030	19.26	19.30	11.10	30.02	0	105	0.00
6	100.050	19.26	19.31	10.95	30.20	0	107	0.00

2017-05-05, Day 25

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
DS sludge g/g	3.35	%
polymer concentration	2.00	g/l
polymer dosage	11.5	(gpoly/kgsludge)
Weight	55	kg
Time	30	mins

Results								
No.	Sludge volume added (g)	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water/ ml	SS %
8	100.031	19.26	19.31	11.18	30.75	0	102	0.00
9	100.020	19.26	19.32	11.14	29.80	0	105	0.00
10	100.024	19.26	19.30	11.19	30.29	0	102	0.00

2017-05-11, Day 26

Experimental conditions		
sludge volume	100	g
sludge density	1.00	kg/l
DS sludge g/g	3.35	%
polymer concentration	2.00	g/l
polymer dosage	11.5	(gpoly/kgsludge)
Weight	55	/kg
Time	30	mins

Results								
polymer concentration	Polymer type	Volume polymer needed/ml	Volume polymer added/ml	Wet cake weight /g	DS %	sludge settlement /ml	Filtered water/ ml	SS %
2.00	Z8180	19.26	19.26	11.13	29.53	0	105	0.00
2.00	Z7587	19.30	19.33	11.06	29.87	0	102	0.00
2.00	Z8190	19.25	19.25	11.19	29.93	0	102	0.00