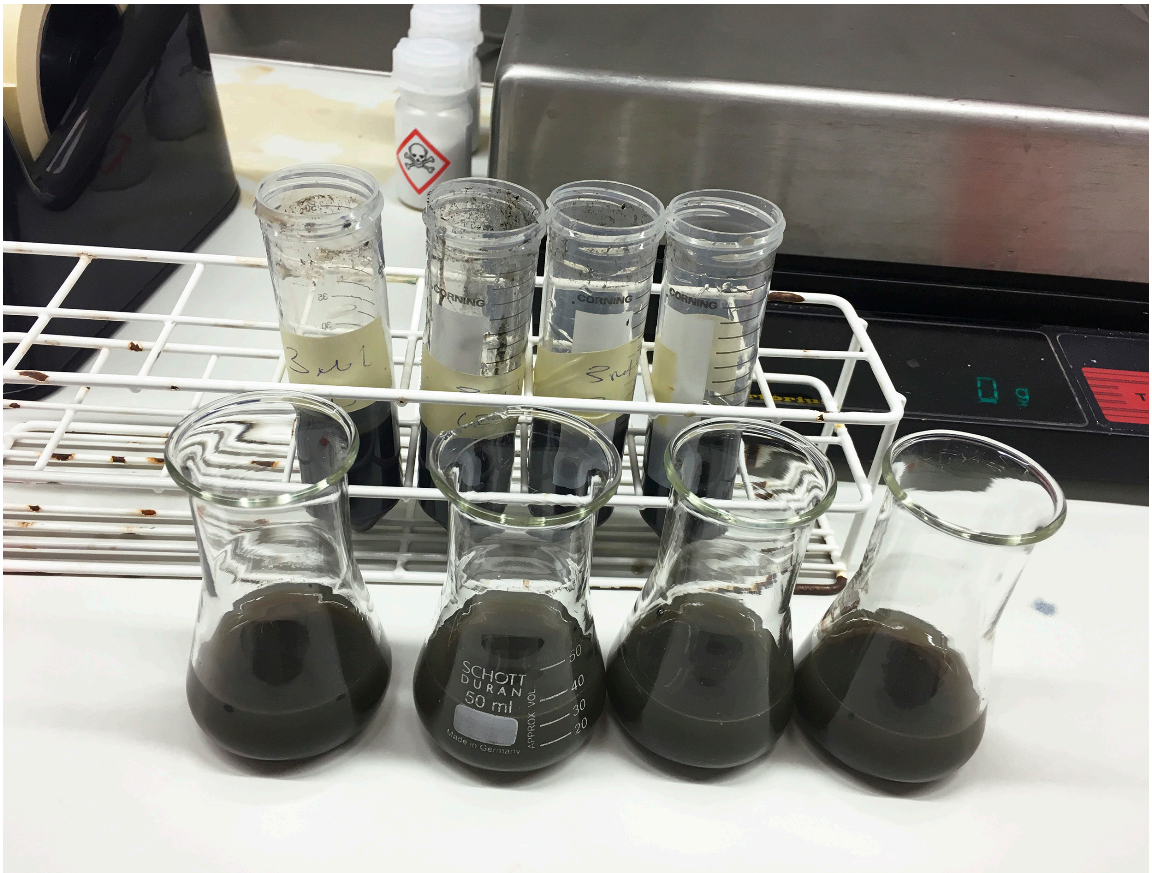
Methods for Evaluating Dewatering Properties of Sewage Sludge



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Preface

I am extremely grateful for the opportunity to work on this thesis project. It has been both enlightening and challenging. Special gratitude to my academic supervisor Åsa Davidsson, for giving me the opportunity to work on this topic, supervising my work and for supporting me through all this thesis period.

I would like to appreciate the great assistance during the laboratory work rendered to me by Gertrud Persson for being so patient and helpful during the whole thesis period. Thanks to Källby wastewater treatment facility for being generous enough to let me pick sludge from the treatment plant whenever it was needed.

I would like to thank the Swedish Institute Study Scholarship (SISS) for giving me this opportunity of studying her in Sweden a master that I am deeply passionate about, it would have not been possible without their scholarship.

I am forever grateful to my family who supported me all the time since birth. My dad Mohamed for supporting & believing in me, my mom Eman who allowed me to pursue my dreams although it was hard to let me go. My sweetest sister Hanadi for loving, supporting me unconditionally, and baby brother Merghani, Uncle Osman, my grandma, aunties and cousins.

The warmest thanks, love and appreciation for my best friends Rawaa, Hibat, Tawhed, Mona , Rana, Muez and Alhagarat for always being there for me through all the joy and sad moments. Great thanks to all my friends here in Sweden Cathy, Jevie, Jago for being there, thanks to all my classmates of the master program, my corridor mates, my old friends from University of Khartoum, which forever will be the warmest place on Earth.

Summary

After the sewage wastewater is collected from different households and directed to the treatment plants, it goes through several processes, which are physical, chemical and biological. The different processes remove the contaminant, and produce a semi-solid material named sludge. Sludge has a huge amount of liquid. Disposing this sludge with no further treatment is a very costly procedure and presents an environmental hazard. Further treatment of the sludge reduces the liquid volume, and furthermore reduce the transportation cost.

However, different techniques are evolving nowadays in large scale, but further investigation is needed of the sludge dewatering properties on the small scale. These laboratory scale methods reliability compared to full scale is a milestone due to lack of knowledge in this area.

In this thesis work, attempts were applied to find methods for dewatering the sludge on lab scale, and then evaluate these different methods based on different criteria. The thesis was divided into two part: literature reviewing and laboratory work. From the literature, seven sludge dewatering methods were found: electro-dewatering, dewatering by osmosis, network strength, ultra-high-pressure filtration (UPF), capillary suction time (CST), centrifuge and lastly pressure filtration test. The first four methods were evaluated based on the information found in the literature. The criteria used for evaluating the methods were: time required and how comparable the obtained results are to large scale. The network strength method required around 24 hours until obtaining the results. The method concept was new and gave abundant data about the sludge dewatering properties. For this reason, network strength is considered an interesting method for further studies.

The lab work included three methods found in the literature, which were CST, centrifuge and pressure filtration test (PFT). The sludge was firstly conditioned using two type of polymers from Kemira. Then lab-scale dewatering methods were applied. The results were obtained from both CST and centrifuge. The pressure filtration test (PFT) faced some technical difficulties regarding filtrating the sludge sample. The three methods were evaluated based on certain criteria.

The criteria used for evaluating the methods used in the lab were: time required, space requirement, simplicity, and the reliability of the results. Based on the evaluation, CST test had a very simple methodology compared with others and consumed less time (few minutes). However, the centrifugation studied the solid content in the supernatant and dry solid content in the obtained sludge cake. These two are important parameters in studying efficiency of the sludge dewaterability.

At last, the aim of this thesis work was accomplished. The different methods were evaluated based on certain criteria. The CST test could be recommended due to its simplicity, short time required to conduct the test, easiness and direct obtaining of the results.

Table of Contents

List of abbreviation

BOD-Biological oxygen demand

CST- Capillary suction time

DS-Dry solid content

EPS-Extracellular polymeric substances

g/kg DS - gram per kg -dry solid weight

PEOD-Pressurized electro-osmotic dewatering

PFT-Pressure filtration test

SS-Suspended solid content

UHP-Ultra high-pressure

TS-Total solid content

WWTP-Wastewater treatment plant

List of Figures

List of Tables

1 Introduction

After the sewage wastewater is collected from different households and directed to the treatment plants, it goes through several processes: physical, chemical and biological. The different processes remove the contaminants, resulting in a sludge. Sludge is a semi-solid material with a huge amount of liquid. Disposing this sludge with no further treatment is a very costly procedure and furthermore presents an environmental hazard. Therefore, further treatment is required.

Before sludge is thickened and dewatered, it undergoes a conditioning procedure. The sludge conditioning is generally known as a process to fasten the dewatering step (Novak, 2006). The sludge is conditioned chemically by using organic polymers or inorganic chemicals, which congregates the fine particles (Turovskiy & Mathai, 2006). The dose of the polymer is a crucial factor in sludge dewatering and is determined by carrying out pilot studies (Novak, 2006).

In present, anaerobic digestion reduces a large amount of the organic matters, and at the same time produces biogas. However, sludge is still left to be handled; usually dewatering the sludge gives a significant reduction of the sludge volume and furthermore reduces the handling cost. Optimizing sludge dewatering is thus a very important point.

However, different wastewater treatment techniques are evolving nowadays together with digester operation optimizing; give rise to new sludge. The dewatering properties of this new sludge need to be investigated. The different sludges need to be investigated in Laboratory scale. This laboratory scale methods reliability compared to full scale presents a bottleneck due to lack of knowledge in this area.

1.1 Problem description

An important matter like sludge dewatering cost an enormous amount of money to be handled. Before the sludge is dewatered, the sludge properties could be tested on small scale. This is a very important step to have a further plan on how to handle sludge on a large scale. The methods used for sludge dewatering on a small scale have to be evaluated

1.2 Aim

The main objective of this thesis is to compile and evaluate methods that test the dewatering properties of sewage sludge in a small scale (laboratory scale). The criteria for evaluating the methods are ; the time used to conduct the experiment, space required , simplicity of the method, reliability of the results and how comparable are the laboratory scale results to the full-scale results.

1.3 Methodology

The methodology used for this thesis is both literature reviewing and laboratory work. The literature reviewing was accomplished by using different databases including LUBsearch, Google scholar, ScienceDirect and others. The literature part discusses the chosen methods for dewatering the sludge in laboratory scale, and evaluate the methods based on different criteria.

A laboratory work was carried out by using the available resources to conduct experiment. Every experiment was repeated three times to have results that are more reliable. From the obtained results and how the method was applied, the methods were evaluated.

2 Sludge dewatering

2.1 Sludge dewaterability

Sludge dewatering is defined as separation of solid phase from the liquid, therefore to have the least possible moisture content in the solid phase and to have least possible solid particles in the liquid is important. Large amount of sludge is costly to handle; hence the sludge should be dewatered (Rao et al., 2017).

The two factors, which affects the dewaterability is the equip

ment used for the dewatering and the sludge type itself (Turovskiy & Mathai, 2006). The dewatering is mainly performed mechanically by using filtration or centrifugation. For enhancing the dewaterability chemicals are used, furthermore it boosts the quality of filtrate (Turovskiy & Mathai, 2006).

Tsang and Vesilind (1990) have divided moisture in sludge into four moisture types; free moisture which is not bounded to any solid particles. Oppositely is the bound moisture, which is chemically attached to the solid particles. The remaining ones are interstitial moisture and surface moisture; which is the moisture held between the floc particles when the sludge is suspended (capillary moisture). The last one is moisture held by adhesion and adsorption. Based on this, the bound moisture needs more energy to break and the smallest to the free one (Tsang & Vesilind, 1990).

Gravity settling is used to remove the free water from the sludge, meanwhile mechanical dewatering is more effective in removing the interstitial water from the sludge particles (Andreoli *et al*., 2007). As for the bound water, only a fair amount is removed by high temperature drying (Novak, 2006).

2.2 Types of sludge

Sludge is divided to different types based on treatment procedure in the treatment plants. Generally, it is grouped to three major types: primary sludge, secondary and chemical sludge.

2.2.1 Primary sludge

Commonly the primary treatment consists of physical mechanical processes, in which the solid particle settles in tanks after the grit-chamber and the screening steps (Turovskiy & Mathai, 2006). The primary treatment removes about 50-70% of the total solids and 30-40% of the BOD (Hammer, 2014). The resulting sludge from this step contains 2-7% solids. This type of sludge is faster to dewater compared with the other sludge types. This is due to its consistency of particles and debris and requires low conditioning and a drier cake is resulted (Lee *et al.,* 2005).

2.2.2 Secondary sludge

Secondary sludge or biological sludge is produced from the biological treatment namely trickling filter and activated sludge (Lee *et al*., 2005). The biological treatment is carried out by the microorganisms, which feed on soluble and insoluble organics (Turovskiy & Mathai, 2006). The secondary sludge is more homogenous and less dense than primary sludge, as it consists of flocs from relatively similar and equal sizes and composition (Andreoli *et al*., 2007).

The solid concentrations in dry solids weight is approximately 0.4-1.5% for the activated sludge and 1-4% for the trickling filter (Turovskiy & Mathai, 2006). The biological sludge is harder to dewater than primary sludge due to the light biological flocs (Turovskiy & Mathai, 2006).

2.2.3 Chemical sludge

Chemical sludge is known as the tertiary sludge which results from the chemical precipitation and filtration procedure (Andreoli *et al*., 2007). This chemical sludge contains mostly chemical precipitates, maybe some heavy metals, and other contaminants (Turovskiy & Mathai, 2006).

2.3 Sludge characterization

The characteristics of sludge is one of the important parameters in designing the sludge treatment system. As found by Andreoli *et al*. (2007) different factors affect the sludge characteristics; namely the type of the raw wastewater introduced to the plant, the stormwater inflow, quantity of other types of wastewater (industrial), contaminants from the ground, groundwater infiltration, and lastly the treatment procedure used for the wastewater and the detention time at the clarifiers.

2.3.1 Primary sludge

Fresh primary sludge as described by Lee *et al*.,(2005) is mostly gray to light brown, and it consists from a wide range of solids size and composition. The high content of the organic matters causes the primary sludge decay and it becomes more septic. One can distinguish the fresh primary sludge from decayed primary sludge by the change of its color to a dark gray or black color plus the sour odor (Lee *et al.,* 2005).

2.3.2 Activated sludge

Activated sludge has a generally brownish color and flocculant in appearance with an inoffensive odor as described by Lee *et al*., (2005). The activated sludge mostly consists of bacterial cells, which are challenging to dewater. The thickening step is a crucial step due to the low solid concentration and relatively high quantity (Turovskiy & Mathai, 2006). To elaborate the mechanical thickening (gravity belt thickening) can raise the solid concentration up to 5% and decrease the volume to a fifth (Turovskiy & Mathai, 2006).

2.4 Physical properties of sludge

The physical properties of the sludge are one of the important factors for treating the sludge, and planning for the sludge treatment. In Table 2.1 below are found common physical parameters for primary and activated sludge.

Table 2-1 The physical parameters of the sludge for both the primary and the activated sludge. (Source (Turovskiy & Mathai, 2006))

Sludge type	Density (g/ cm^3)	Particles size (mm)
Primary sludge	1.0 – 1.03	Less than 1 mm for 50 to 80% of the sludge. Between 1-7 mm for 9-33% of the sludge. Larger than 7 mm for 5-7% of the sludge.
Activated sludge	1.0	Less than 0.2 mm for 90% of the sludge. Between 0.2- 1 mm for 8% of the sludge. 1 mm for 1.6% of the sludge. 3 mm for 0.4% of the sludge.

From the Table 2.1, it can be seen that 80% of primary sludge has a particle size of less than 1 mm, and only 5% has particles larger than 7 mm. 90% of the activated sludge has particles size less than 0.2 mm and only 0.4% has a size of 0.4 mm.

2.5 Chemical properties of the sludge

The main contaminants in the sludge are metals, trace organic contaminants and pathogenic organisms (Andreoli *et al*., 2007). The quantity of these three varies based on the raw wastewater characteristics and the process of the treatment (Andreoli *et al*., 2007). The pathogens organics could be from a human or animal source. The amount of the pathogens in wastewater depends on different factors such as the sanitation status, geography of the area, agro-industries, and socioeconomic status of the residents (Andreoli *et al*., 2007.)

Another affecting parameter is the type of the wastewater, for instance domestic wastewater has a very low heavy metal and chemical contaminants. These parameters increase for industrial wastewater (Lee *et al*., 2005).

As for the trace organics, the source is the chemical and pharmaceutical industries, laundries and pesticide formulation etc., those organics lead to pollution of soil, water and plants (Andreoli *et al*., 2007).

2.6 Sludge treatment

The sludge treatment is simply summarized as removing the water (reject water), stabilize the sludge and kill off pathogenic organisms (Turovskiy & Mathai, 2006). In theory the three step looks simple and ready to execute but in reality, the different steps take a lot of time and many trials to choose the right method. The sludge treatment methods are thickening, stabilizing and finally dewatering the sludge (Andreoli *et al*., 2007; Turovskiy & Mathai, 2006; Sanin *et al*., 2011).

The raw sludge (untreated sludge) as shown from Figure 2.1 undergoes several steps before the final disposal. The influent sludge is firstly thickened, stabilized, and then followed by conditioning step. The sludge is then dewatered and incinerated before the last step. In the following sections Figure 2.1 is further explained

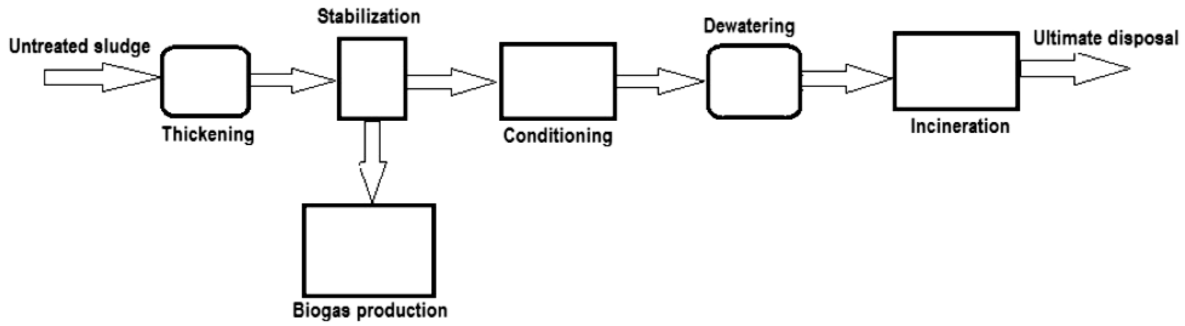

Figure 2.1 Typical sludge treatment steps.

2.6.1 Sludge thickening

The sludge thickening procedure is increasing the solids of the sludge concentration and reducing the volume of the water within the sludge (Turovskiy & Mathai, 2006). The sludge thickening has a significant effect on the cost of the following treatment steps (Andreoli *et al*., 2007). The sludge is thickened on treatment plant by using gravity thickening, floatation, thickening by drainage and centrifuges (Sanin *et al*., 2011).

2.6.2 Sludge stabilization

The sludge is stabilized due to its uncomfortable odour, the probability of containing heavy metal ions and pathogens (Turovskiy & Mathai, 2006). The stabilization stops the biological activity and reduces the pathogens (Turovskiy & Mathai, 2006). The sludge is usually stabilized by using one of these methods: anaerobic digestion, aerobic stabilization, thermal and chemical oxidation, and pasteurization (Andreoli *et al*., 2007).

2.6.3 Sludge conditioning

The conditioning step is carried out before the dewatering and the purpose is to affect the efficiency of the dewatering procedure (Sanin *et al*., 2011). The aim of using conditioners is to break the jelly-like layer. Furthermore, to alter the size of the particles and their distribution, the interaction within the sludge particles and the charges of the sludge particles (Lee *et al.,* 2005).

As mentioned in (Andreoli *et al*., 2007), the specific surface of the particles increases the hydration degree and the demand for chemicals and dewatering resistance increases proportionally, hence the importance of conditioning lies in increasing the particle size through binding small particles together and forming large particles. The quantity of the conditioner differs relatively with the characteristic of the sludge and the equipment used for dewatering (Lee *et al.,* 2005).

2.6.4 Dewaterability of sludge

Sludge dewatering is removing the water from the sludge using mechanical methods (Sanin *et al*., 2011). The particle size affects the efficiency of separating the water from the sludge; small particles of sludge have a low separation efficiency (Turovskiy & Mathai, 2006).

The dewatering step reduces the volume of the sludge more than thickening, and its efficiency affect the energy required for the thermal drying or incineration for evaporating the surplus moisture in the sludge (Lee *et al.,* 2005). Consequently, sludge treatment methods that results in smaller sludge particles affect the dewaterability of the sludge.

As shown from the Figure 2.1, after the dewatering step is the disposal. The transportation cost to the disposal place depends on the volume produced from the dewatering. Thus, optimizing the dewatering step is very crucial; it improves the sludge handling conditions, increases the heating capacity of the sludge for the following incineration step and lastly reduces the transportation cost (Andreoli *et al*., 2007). However, the incineration step is not commonly applied.

Mikkelsen & Keiding (2002) and Nellenschulte & Kayser (1997) carried out studies about parameters affecting the sludge dewaterability. Both studies showed that major parameters affecting the sludge dewaterability are the sludge particles size distribution, bound water, organic solid content and the extracellular polymeric substances (EPS). However, the best dewaterability is attained only by optimizing the chemical treatment and the mechanical equipment operation as well (Turovskiy & Mathai, 2006).

2.6.5 Incineration

Incineration is a complete combustion; it is a rapid exothermic oxidation of combustible elements in the sludge as described by Turovskiy & Mathai (2006). During this process, the organic matters are changed to oxidized end products (primarily carbon dioxide), water vapor and ash (Turovskiy & Mathai, 2006).

The incineration process reduces the volume and weight of wet sludge cake by 95% and furthermore reduces the disposal requirements. It also reduces the toxins and destructs the pathogens (Turovskiy & Mathai, 2006).

2.7 Methods of dewatering sludge on large scale

The sludge dewatering is a crucial step and has a significant effect on the sludge handling afterwards. Thus, the methods used for sludge dewatering are continuously evolving. The belt filter press, centrifuge and drying beds are the most common methods for sludge dewatering (Turovskiy & Mathai, 2006).

2.7.1 Belt filter press

A belt filter press is well described by Sanin *et al*., (2011) as a continuously fed sludge dewatering machine. It has two continues porous belts which pass over a series of rollers for pressing the water out of the sludge condensed between the belts. The belt filter consists of a gravity drainage section where sludge is thickened and mechanically applied pressure section where the sludge is squeezed between the opposing porous belts (Sanin *et al*., 2011).

Firstly, the chemical conditioner is added into the sludge at the sludge polymer mixer located at the feed line to the press. Secondly, the sludge is directed to the gravity drainage zone for thickening. Lastly, at the applied pressure zone, a low pressure is applied first and then followed by a high pressure where sludge is exposed to shearing forces as the belts pass through series of rollers. The sludge feed should be at a uniform rate (Andreoli *et al*., 2007). Figure 2.2 below shows belt filter press machine for sludge dewatering.

The belt filter is a popular equipment for dewatering as it has a low cost, utilize less chemical flocculation of sludge compared with other methods, low operational cost and available in small and medium sizes (Hammer, 2014).

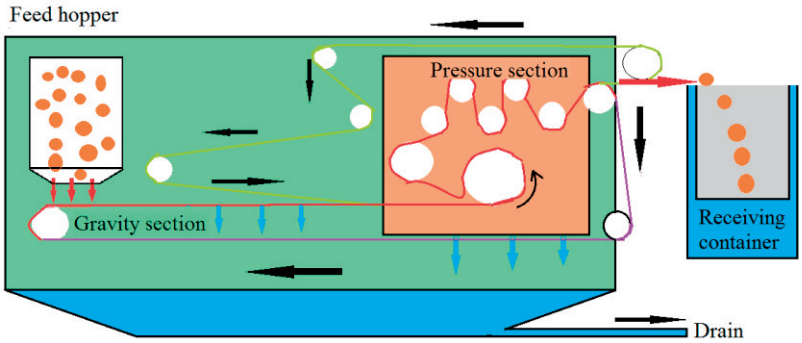

Figure 2.2 Belt filter press for sludge dewatering.

2.7.2 Centrifuges

Centrifuges are very common in municipal wastewater treatment plants in the United States of America and Europe (Andreoli *et al*., 2007). Centrifuges are signed for dewatering the primary and activated sludge (Turovskiy & Mathai, 2006). The sludge particles and moisture are separated under the impact of the centrifugal forces, the basic type of centrifuges is the solid-bowl (Sanin *et al*., 2011). Firstly, the sludge solids are settled by a higher speed than gravity speed. Then followed, by the compaction stage where the sustainable centrifugal force separates the capillary moisture from sludge particles (Andreoli *et al*., 2007). Lastly the cake is removed, the sludge is fed to the unit continuously. The large particles are captured more compared to the finer particles. However, adding chemical conditioners enhance the solid capturing (Sanin *et al*., 2011).

Centrifuges are used for both thickening and dewatering. The centrifuges efficiency depends on the sludge type, solids concentration, type of conditioning, sludge volatile solids concentration, sludge feed rate and temperature (Andreoli *et al*., 2007). Figure 2.3 below shows centrifuge machine for sludge dewatering.

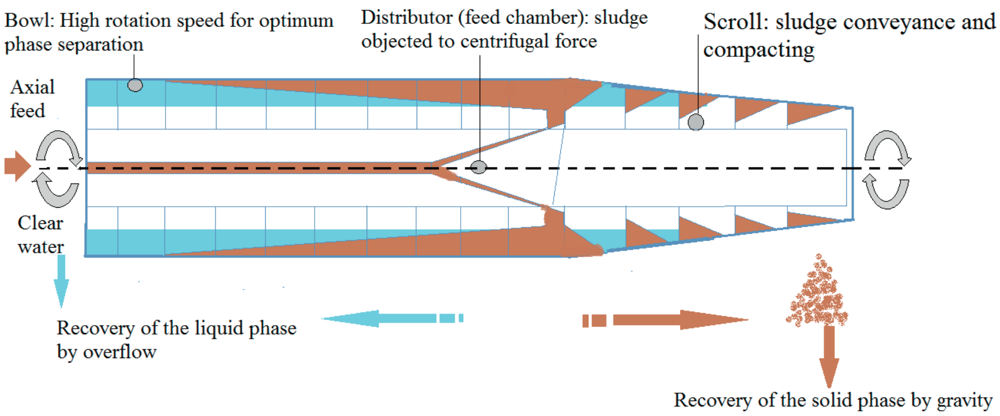

Figure 2.3 Centrifuge for sludge dewatering.

Comparison between the belt filter press and centrifuges

The most dominant technologies are belt filter presses and centrifuges. A study was carried out by Mamais *et al.* (2006) on evaluating the two technologies by using full-scale data from two different wastewater treatment plants. From the study, the annual sludge dewatering and disposal cost for a small to medium WWTP and a medium to a large WWTP was considered higher for the belt filter press. As the belt filter press costed 106-147 Euro/ton DS and only 82-114 Euro/ton DS for centrifuges. Another finding from the study was that centrifuges tend to obtain drier solids and higher reject water volume at a lower polymer consumption rate. Although the capital cost for the centrifuges was higher than for the belt filter press, the maintenance cost and long-term operation cost was significantly lower than for belt filter press (Mamais *et al*., 2006).

2.7.3 Drying beds

Drying beds are considered one of the famous methods used to dewater the sludge in the Eastern Europe countries and United States of America (Cheremisinoff, 2002). The method is based on thermal energy and is usually used on well digested sludge. The drying beds have a gravel base, topped with sand layer and drainage joint pipes underneath (Cheremisinoff, 2002). Commonly, the drying bed is opened to the air, but could be built with the green houses in colder climate conditions. The sludge is left to dry by evaporation from top and released water from below is directed by the drainage pipes as described by Cheremisinoff (2002). This method is simple and has a low capital cost, low energy and chemical consumption. On the other hand, it requires a large area and odor problem if located close to residual areas and weather conditions could be a limitation factors for its performance. However, the greenhouses performance is not limited with the last two (Cheremisinoff, 2002). Figure 2.4 below shows drying bed for sludge dewatering.

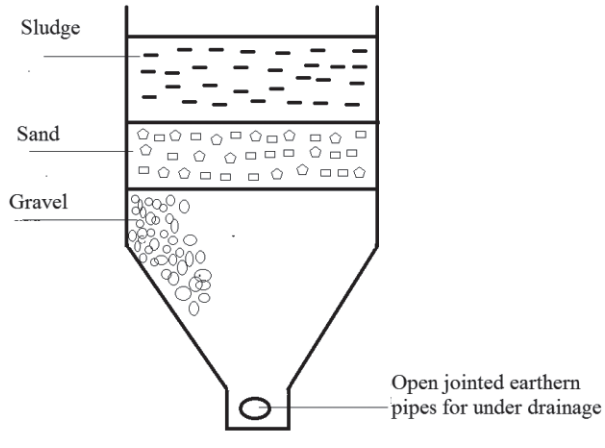

Figure 2.4 Drying bed for sludge dewatering.

2.7.4 Pressurized electro-osmotic dewatering (PEOD)

Pressurized electro-osmotic dewatering is considered as one of the most efficient technologies as described by Rao *et al*. (2017). It can remove moisture content up to 60% by using energy of 0.06-0.643 kWh per kilogram removed water. The energy used for thermal drying of sludge dewatering is 0.617- 1.2 kWh per kilogram removed water. The PEOD consumes less energy than for thermal drying (Rao *et al*., 2017). The disadvantage of using PEOD is that, the dry sludge near the anode plate results in poor effect of dewatering in the later stages and due to corrosion phenomenon, the electrode plates have short life (Rao *et al*., 2017).

3 Lab-scale dewatering characterization methods

This chapter explains the methods which were obtained from the literature reviewing for sludge dewatering characterization in lab scale. The different methods are explained below and evaluated based on the reports found for these methods.

3.1 Methodology for literature reviewing

The literature reviewing was achieved by using several databases including LUBsearch, Google scholar, Science Direct and others.

The keywords that were used for literature reviewing are found below.

sludge dewatering, dewatering of the sludge, sewage sludge, laboratory scale sludge treatment, dewatering sludge, dewatering sewage sludge, CST, capillary suction time test, centrifuge, lab-centrifuge, rheology, polymers conditioning, sludge conditioning, centrifuge on lab scale, evaluation of lab experiments, CST evaluation, mechanical dewatering evaluation, sludge dewatering at lab, lab scale dewatering process, sludge dewatering methods at lab.

3.1.1 Electro-dewatering

Conrardy *et al.* (2016) used an electro-dewatering method. The method principle is applying compression on the sample of the sludge combined with electric field. The electric energy forms a heating source for catalyzing sludge particles to free the bound water. The electro-dewatering method has a high risk of ohmic heating and electrode corrosion. The filtrate and the filter cake could be alkalinized and acidified due to electrolysis reactions (Conrardy *et al.*, 2016).

3.1.2 Osmosis-dewatering

Dewatering of municipal sludge by osmosis means removing water from the sludge by using the difference in the osmotic pressure of two solutions. Pugsley and Cheng (1981) used this method. The osmotic pressure represents the main force in moving the water from one solution to the other.

Osmotic pressure difference with a semipermeable membrane method was used in this method and no chemicals or organic sludge conditioners were used. Pugsley and Cheng (1981) placed the sludge directly on the semipermeable membrane and on the other side a high concentrated brine (strong saline solution) stream was flowing. Figure 3.1 below shows a sketch for the Osmosis dewatering method.

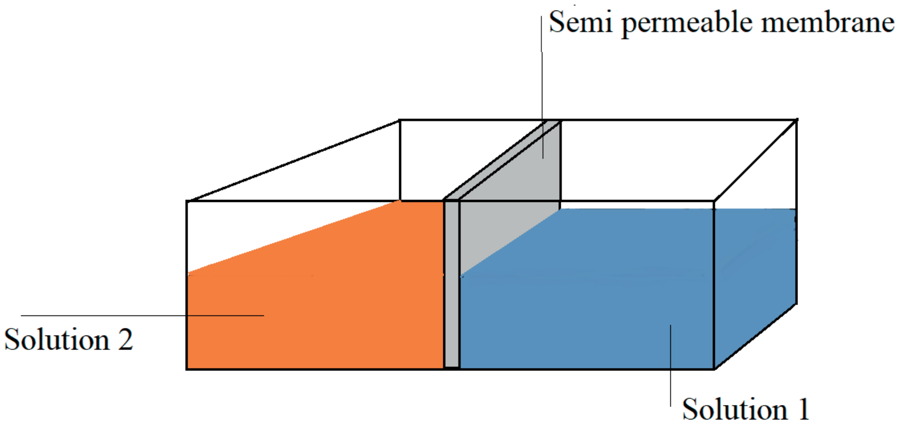

Figure 3.1 Osmosis pressure method for sludge dewatering.

3.1.3 Network strength of sludge

The objective of this method is using the rheology principle of the sludge to describe how strong the network structure of the specific sludge is and the required energy to break this bond. Ömerci & Abu-Orf (2005) carried out this method and found that the network strength of the sludge is linked to the sludge dewaterability and filterability.

The network strength in this study was measured using Floccky Instrument (Koei Industries Inc.). Figure 3.2 shows the Floccky Instrument used for this method.

It was measured at different polymer doses, followed by measuring the dewaterability using Capillary suction time (CST) and filtration test. At the optimum dose, the network strength drops as the energy used to change the water status is more than the input energy due to the binding capacity (Ömerci & Abu-Orf, 2005).

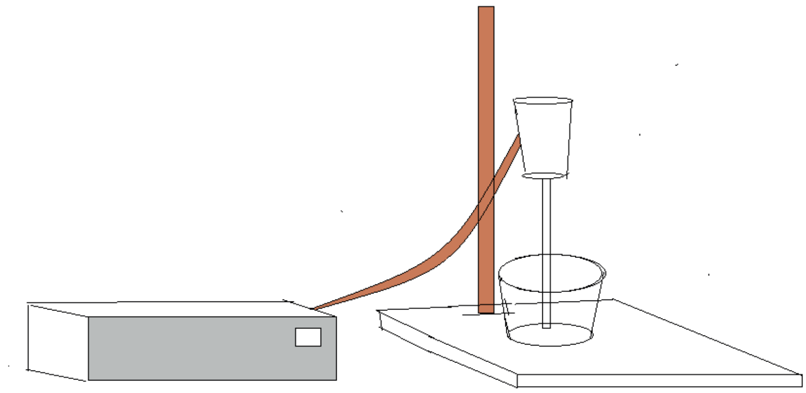

Figure 3.2 Floccky Instrument for measuring the network strength of the sludge.

3.1.4 Ultra-high-pressure filtration (UHP)

An ultra-high-pressure device was used for this method to dewater the sludge. Rao *et al*. (2017) mentioned that the sludge was conditioned first and then the ultra-high pressure was applied on the sample. Figure 3.3 shows the ultra-high pressure device. The obtained dry cake had a reduction of moisture content to half (50%). From the obtained results, it can be noticed that the dry solid content was even higher than the one obtained in large scale (20 to 25 %). (Rao *et al*., 2017).

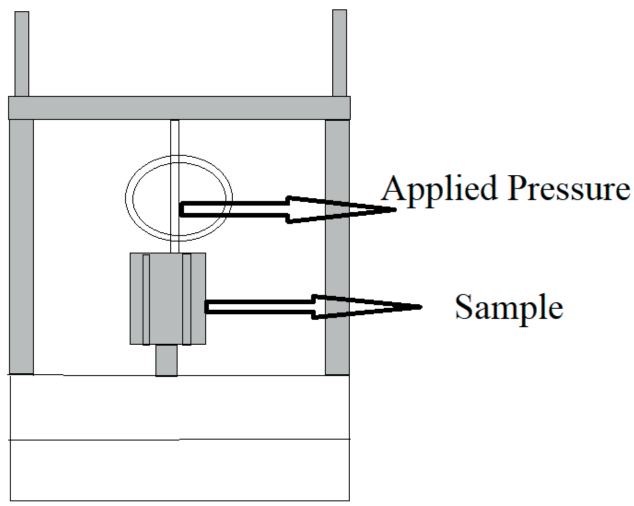

Figure 3.3 Ultra-high pressure device.

3.1.5 Capillary suction time (CST)

Gale and Baskerville (1967) firstly developed capillary suction time, which is considered the most common dewatering characteristic. The capillary suction time measures the filterability and easiness of removing moisture from slurry and sludge (Gale & Baskerville, 1967; Vesilind, 1998).

The test measures the time consumed by the free water to go from one fixed point to another fixed point using suction paper as a medium. This method is well known for its cost effectiveness besides being fast and simple to conduct (Scholz, 2005; Dentel & Abuorf, 1995).

Scholz (2005) described that the water flow in the paper is physically similar to the water flow in porous media. The flow depends on the material balance between the water and the Darcy's law. As the hydraulic conductivity, the suction of the paper and the suspension are all connected to the water content.

The CST test can be used as a method to determine the optimum dose of polymer for chemical conditioning, which results in an optimal dewatering property (Jin *et al.,* 2004). The CST provides an abundant data of the chemicals' effects on the sludge dewaterability (Baskerville, 1977) (Swanwick, 1972). Therefore, this method is considered very handy for testing dewaterability properties in numerous industrial, chemical and environmental applications (Scholz, 2005). Furthermore, it was used for more than 20 years in wastewater and water treatment to evaluate the chemical conditioning on the sludge and detecting the dewaterability (Vesilind, 1988).

On the other hand, another study carried out by Chen *et al.* (1996) showed that CST could not be used directly to evaluate the bound water in the sludge, but rather be a fundamental measurement for the sludge dewaterability as described by Vesilind (1988).

Moreover, based on experimental studies carried out by Karr & Keinath (1978), Mikkelsen & Keiding (2002) and Novak *et al.* (1998) it was found that parameters like particle size, surface characterization, the structure of the flocs and filter paper structure has a major effect on the CST results. Therefore, the bound water content is not enough to describe how the water is separated from the solid part of the sludge.

3.1.6 Centrifuge

A centrifuge is a common device used in medical and chemical engineering laboratories (Andreoli *et al*., 2007). The sludge particles and moisture are separated under the impact of the centrifugal forces; centrifugal force separates the capillary moisture from sludge particles. There are different types of centrifuge devices but they share the same parameters. Temperature, speed and centrifuge time can all be set on these devices (Sanin *et al*., 2011).

After the device stops, samples are taken to separate supernatant from obtained sludge cake. The supernatant water volume and sludge cake weight are then measured. As described by Peeters *et al.* (2011) suspended solid analysis can be executed on the supernatant water, to measure the solid substance in the water phase. A dry solid analysis (DS) is carried out for the solid phase. The centrifuges efficiency depends on the sludge type, solids concentration, type of conditioning, sludge volatile solids concentration, and temperature (Lee *et al*., 2005). It is important to note that the objective of sludge dewatering is to obtain less solid in the supernatant phase and a drier cake (Andreoli *et al*., 2007).

3.1.7 Pressure filtration test

The principle of pressure filtration test mimics the process applied on large-scale, where hydraulic or mechanical forces are applied to press the sludge. A master thesis study was accomplished by Guo in Chalmers university (2017), where Guo used the same principle of applying pressure to study the sludge dewaterability. A device designed by Gryaab AB was used for the study. The device was designed with a purpose of pressing the water out of the sludge resulting in a sludge cake formation. The device has a vessel where the sample is placed, and the pressure is produced by stacking dead loads on the liver. The applied load was gradually added to guarantee a smooth process (Guo, 2017).

3.2 Evaluation of methods from literature reviewing

The methods found from the literature reviewing are evaluated below. The first four methods are evaluated based on two criteria: time required to conduct experiment and how comparable the obtained results to the large scale results.

The other three methods were applied in the laboratory, and further explanations are provided in **Chapter 4** followed by methods evaluation in **Chapter 5**.

Table 3-1 Evaluation of methods found from literature reviewing

Method	**Time required**	**Comments**	**Reference**
Electro-dewatering	Less than 24 hours.	Cake dryness ranged between (25 – 45 %).	(Conrardy *et al*., 2016)
Dewatering by osmosis	Less than 24 hours.	Water content is reduced down to 70% or less.	(Pugsley and Cheng, 1981)
Network strength	More than 24 hours.	The method was used on large scale and had similar results as for laboratory scale. The same behavior of network strength was noticed at the optimum dose of polymer for both large and small scale.	(Ömerci & Abu-Orf, 2005)
UHP	More than 24 hours.	Water content is reduced to 50%.	(Rao *et al*., 2017)

From Table 3.1, it can be noticed that the time required to conduct this experiments is used as a criteria to assess these methods. The four methods did not require a large space to conduct the experiments. The different equipment used had a convenient size and were suitable for the laboratory room.

The time used for conducting the actual work in the laboratory was not mentioned in the references mentioned above. However, the DS analysis consumes 24 hours till obtaining the results. Both electro-dewatering and dewatering by osmosis had no DS analysis included, therefore both were estimated to consume less than 24 hours (roughly an hour) (Pugsley and Cheng, 1981; Conrardy *et al*., 2016). On the other hand, Network strength and UHP were estimated to consume more than 24 hours; as a DS analysis was carried out on the obtained sludge cake.

For the osmosis dewatering method, the sludge sample had a water content reduction down to 70% which is close to the obtained results in large scale (65% - 85%). For the electro dewatering, the dry solid content resulted from 25 % to 45%. This result is close to the large scale results (25- 30%). The ultra-high pressure method had a water content reduction down to 50% which is less than the obtained results from the large scale. The network strength method was applied on large scale as well; the results obtained from both small and large scale had approximately the same behavior. Both small and large scale had low network strength at the optimum dose of the polymer.

4 Sludge dewatering methods applied in laboratory

The content of this work included sampling and lab analysis of the sludge, interpretation and collection of data. The dewatering properties of the sludge were evaluated by using two different methods, which are the **Capillary suction time (CST)** method and the **Centrifuge test.**

The pressure filtration test was also carried out once, but due to some difficulties explained below it was not preceded.

During the Capillary suction time, the time was recorded and was double checked by the visual observation of the free water (observing by the abstract eye).

As for the Centrifuge test, the following was measured:

- Weight of sludge cake.
- Volume of supernatant water.
- Suspended solid content in the supernatant (SS analysis)
- Dry solid content for sludge cake (DS analysis).

The experimental work was divided into two stages; where in each stage a different polymer concentration was used. For the first stage, the dose of the polymer had a concentration of 5 g/l. Both centrifuge and CST test were executed. For the centrifuge test, the above-mentioned measurements were carried out except for the suspended solid analysis.

The second stage of the experiment has a polymer concentration of 2 g/l and the suspended solid content was analyzed for the reject water (supernatant). Furthermore, different centrifugal time was used to study the behavior of the sludge dewaterability with the different centrifuging time.

For the CST test, it took several numbers of trial and error experiments to get reliable and repeatable results as the device used is an old one and had faced some problem with the electricity connection. Therefore, visual observations (with abstract eye) were done as well to double check the results obtained on the device.

Two different type of cationic polymers were used to condition the sludge. The purpose of adding polymers is to condense the sludge solids and separate the rejected water out of the sludge, which leads to a more efficient sludge dewatering process. The sludge was conditioned with cationic polymers from Kemira (C-496 & C-498).

To be noticed; both polymer solution and the total solid (TS) analysis were carried out on daily basis.

4.1.1 Sludge sample and polymer agent

In the following sections, the sludge sampling and polymer solution preparation are explained.

Källby treatment plants

The following information was provided (VA SYD, 2016).
The primary sludge and the activated sludge are both thickened first in a gravity thickener where the water content is reduced by allowing the solid particles to settle at the bottom. The rejected water

from this step is pumped back to the inlet of the plant. The next step for the thickened sludge is the mechanical thickening where water content is further reduced in a drum thickener. The sludge is conditioned and then conveyed to the rotating drum. The rejected water passes through the screen cloth and is directed back to the inlet of the plant. A screw moves the sludge through the drum.
The next stage is the digestion where the organic matter is digested in anaerobic conditions which is achieved by different types of microorganisms and leads to biogas formation. The two digesters perform at 37°C (mesophilic digestion). The total retention time at the digester is 20 days. The digested sludge is transported regularly from the digesters and stored at the sludge thickeners.

The process engineer Ossiansson at Källby WWTP pointed out that currently only one digester is working as they are trying to change the other digester to a thermophilic digestion. As a result of that, the obtained sludge is not degraded enough but Ossiansson assured that this does not affect the sludge dewaterability properties.
The sludge was brought to the laboratory two times. The first time was on 4 April 2018 and the second was on 24 April.
At the first time (4 April), the sludge was used from 4 April to 10 April. During this period, the sludge was stored at 37°C.
For the second time (24 April), the experiment was carried out from 7 May to 11 May. The sludge was stored at 37°C as well.
On the day of conducting the experiments, a 2 liter of a sludge was kept at room temperature.
The TS analysis was carried out daily in the two stages to monitor the sludge quality. For the two periods, the DS of the sludge was approximately the same (6 %)

Polymer

Two-polymer type were used for this study. Both of the polymers are Superfloc C- 490 series which are cationic flocculants and known for conditioning solids for dewatering operations. Polymers (C-496 & C-498) with two-solution percentage were used to conditioning the sludge.

The reason for using two different polymer concentrations is because the first concentration of the polymer was of a high concentration. The 0.5 % polymer solution had a jelly texture, which made it difficult to take the polymer dose using syringe or pipette. Therefore, a more diluted solution of the polymer was prepared for the second part of the study.

During the first period of running the experiment 0.5 % solution for both (C-496 & C-498) polymers was used to condition the sludge. For the second period of conducting the experiment, a 0.2% solution for both the polymers was prepared and used to condition the sludge.

The polymer with 0.5% concentration was prepared as below:

- A 100 ml distilled water was prepared in a small beaker.
- 0.5 g of the polymer was weighed by using the scale.
- The weighed polymer was added to the distilled water in the beaker.
- The stirring rod was placed inside the beaker and the beaker was placed on the magnetic stirrer.
- The magnetic stirrer was set at 1000 rpm for 2 minutes.
- The solution in the beaker was covered by a plastic wrap and left to age for 30 minutes before being used.

The other solution for the second part of the study was prepared by repeating the same previous steps, but only 0.2 g of the polymer was weighed. The polymer solution was prepared for a one-day usage.

Figure 4.1 below shows how the polymer solution was added to the sludge by using syringe.

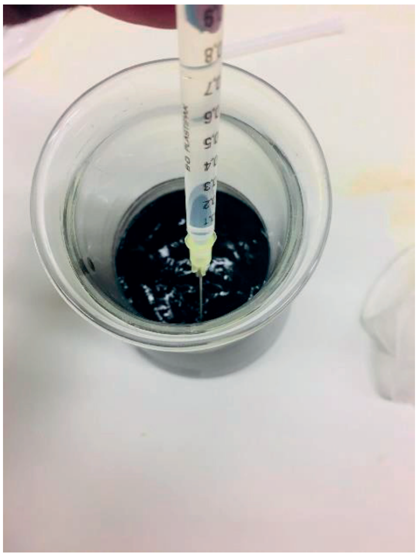

Figure 4.1 Shows how the polymer solution was added to the sludge

The polymer dose for large scale ranges between 3 to 8 g polymer/kg DS of sludge (SNF Floerger , N.d). The first dose of the polymer (0.8 g polymer/kg DS of sludge) was chosen , then the value of the polymer dosage was doubled to observe the effect of the polymer dose increment on the sludge dewaterability. The main objective is to study the effect of using different doses on the sludge dewaterability. For the first stage of the study a 0.8, 1.6, 4 and 8 g polymer/kg DS of sludge were used. The first two polymer dosage were taken below the recommended range (3 to 8 g/kg DS of sludge) to observe the effect of a smaller dose on the sludge dewaterability. For the second stage of the study 0.8, 1.6 and 3.3 g polymer/kg DS of the sludge were used. At the second stage, lower doses of the polymer were used, because it was observed how flocky the conditioned sludge was when the polymer dose was 8 g polymer/kg DS of sludge (Figure 4.1).

Experimental procedure

This section elaborates on the experiment steps for CST and Centrifuge test for this study.

In Appendix A, description of all the used equipment is attached.

Preparation

- The digested sludge was taken from the Källby treatment plant and stored at 37°C.
- 2 l of sludge was taken from the stored sludge and during the whole time of the experiment was kept at room temperature.
- The polymer solution was prepared as described above.
- Three samples were taken (each weight around 20 g of raw sludge) to run the DS analysis on sludge.

Capillary Suction Time (CST-Triton- W.P.R.L Type 92/1)

- A 50 g of sludge was weighed in a beaker, and dose of polymer (0.8, 1.6, 3.3, 4 and 8 g polymer/kg DS sludge) was added and mixed for 2 minutes at 200 rpm. The conditioned sludge was left to rest for 5 minutes.
- A moisturized piece of cloth was passed on the sensors at the plates of the CST equipment.
- A filter paper was placed between the two plates.
- A 5 ml of the conditioned sludge was taken by the syringe and was placed on the cylindrical cell of the CST equipment. The CST has a self-timer, which works when the sludge reaches the first ring on the plate.
- The CST equipment turn off automatically as soon as the water reach the sensor on the outer ring. The seconds on the screen were recorded, and the timer was reset again.
- The sludge in the cylindrical cell was removed carefully without moving the CST equipment.
- The same steps were repeated again for the other doses of polymer.

The experiment was carried out three times per each dose of the polymer to get reliable results.

Centrifuge (Centrifuge Sigma 3-16K)

- 150 g of sludge was weighed in a beaker, the polymer was added to the sludge and was mixed with an intensity of 200 rpm for 2 minutes, and the conditioned sludge was left to rest for 5 minutes.
- Samples of 50 ml each was weighed in the centrifuges tubes.
- The centrifugal tubes were placed inside the centrifuge device, the centrifuge was set to a radius of 4000 rpm for 30 minutes at the first stage of the study. For the second stage the time was for 5 and 15 minutes.
- The obtained cake was separated from the water phase by pouring out the water from the centrifuge tubes into a beaker. During the first stage of the study, the water volume was weighed and the obtained dry cake were collected carefully and taken for dryness analysis (DS).
- At the second stage of the study, the centrifuge time was set at 5 and 15 minutes. The water phase in the centrifugal tubes was poured in a beaker and was taken for suspended solids analysis (SS), and the obtained cake was taken for the dry solid analysis (DS).
- The SS analysis used for this lab work is the Gravimetric method is based on Method 2540 D of *Standard Methods for Examination of Water and Wastewater, 23 rd Edition* (Baird *et al*., 2017).

The used G-force is 1613 for the three different centrifuge times.

Pressure Filter Test (Labox 25)

- 100 gram of sludge was weighed in a beaker, followed by adding the polymer to the sludge and mixing it at 200 rpm for 2 minutes.
- The conditioned sludge was left to rest for 5 minutes.
- The filter cloth No. 71-2155 was placed over the grid in filtrate vat. The sealing was placed on the top of the cloth and the cylinder was fastened into the filtrate vat by turning and tightening the joint manually.
- A 100 ml of conditioned sludge was measured and poured it into the cylinder.
- The cylinder and piston were placed between moving pressing plate and upper pressing plate. The air valve was closed.

- The desired pressure was set in the pressure regulator and a beaker was placed beneath the filtrate hose. The beaker was used to collect the obtained supernatant. The cylinder drive valve was turned up to start pumping.
- The cylinder drive valve was turned off, and the stopwatch was set to record the time used for pressing.
- The air-drying step was set on. By turning the air distribution valve to air blow and opening the air on/off valve by only ¼ of a turn. The stopwatch was set on when the air started coming out of the filtrate hose to record the drying time. The air distribution valve was turned off to stop the drying, followed by turning air on/off valve off.
- The cake discharge step was carried out manually by turning off the cylinder drive valve up in order for the cylinder to be lifted up. Then the cylinder drive was turned off. The limit knob was pulled out. Followed by taking the cylinder out of the filter, and removing filtrate vat from cylinder, the cake was taken out of the cylinder.
- The cake wash process was performed after the pressure cycle. The cylinder was faced downward and held on the hand. A measured amount of the liquid was poured on piston and cylinder. The piston and cylinder were placed back in their position. The cake wash step was carried out similarly as the pressing step.

The available labox device in the lab was used to conduct lime slurry filtration experiment by other students. This was the first attempted to use the device to dewater the sludge. During experiment execution, the sample scattered all over the labox device, lab coat and my face. For that reason, the experiment was not preceded. The reason behind the incident was the inconvenience of the device for pressing the sludge, and some mechanically difficulties.

5 Results and Discussion

As described in previous chapter, the lab work had two stages. In this chapter, the results from first stage and second stage are presented. A comparison between the results obtained from both stages is presented in graphs at the end of this chapter. Lastly, the methods used on the lab are evaluated based on different criteria.

5.1 First stage of study

The polymer solution in this stage had a concentration of 0.5%. The centrifuge time was set for 30 minutes at 4000 rpm and 25°C.

5.1.1 Polymer C-496

Centrifuge test

From the Table 5.1 below it can be seen that the different doses of polymer resulted in approximately the same dry solid content of the cake (13.0 %). The reason behind that could be the long centrifugation time used.

Table 5-1 The results obtained from different dose of the polymer C-496 and DS of the sludge cake for centrifuge test (30 minutes centrifuging time)

Polymer dose (g polymer/ kg DS sludge)	Dry solid content of cake % (Average ± standard deviation)
0.8	13.0 ± 0.2
1.6	13.0 ± 0.2
4.0	13.0 ± 0.1
8.0	12.5 ± 0.1

CST

From the Table 5.2 below, it can be noticed that as the polymer dose increased the time taken by the water to reach the second ring of CST device was shorter. This means the filterability of the sludge increased with polymer dose.

Table 5-2 The results obtained from different dose of the polymer C-496 and average CST in seconds.

Polymer dose (g polymer/ kg DS sludge)	Average of CST (seconds) (Average ± standard deviation)
0.8	352.0 ± 106.1
1.6	325.0 ± 114.6
4.0	250.0 ± 79.1

From Table 5.1 and Table 5.2, the effect of the sludge conditioning was more noticeable for CST results than for centrifuge results.

5.1.2 Polymer C-498

Centrifuge test

It can be noticed from Table 5.3 below, that all the different dose of the polymer resulted in approximately the same DS content around 12.0 %. The reason behind that could be the long centrifugation time used.

Table 5-3 The results obtained from different dose of the polymer C-498 and DS of the sludge cake for centrifuge test (30 minutes centrifuging time)

Polymer dose (g polymer/ kg DS sludge)	Dry solid content % (Average ± standard deviation)
0.8	12.0 ± 0.1
1.6	12.0 ± 0.3
4.0	12.6 ± 0.3
8.0	12.0 ± 0.3

CST test

From the Table 5.4 below, CST decreased with the polymer dose increment. It can be seen a more filterability was noticed as the dose of the polymer increased.

Table 5-4 The results obtained from different dose of the polymer C-498 and average CST in seconds.

Polymer dose (g polymer/ kg DS sludge)	Average of CST (seconds) (Average ± standard deviation)
0.8	325.0 ± 125.0
1.6	337.5 ± 210.3
4.0	275.0 ± 75.0

For both polymers, the fourth dose of the polymer 8 g polymer/kg DS sludge was not executed due to the flocky condition of the sludge. It was difficult to take 5 ml of the sludge by the syringe or the pipette for the CST test as shown in Figure 5.1.

Figure 5.1 The state of the conditioned sludge for dose 8 g/kg DS sludge for the two polymer type.

The CST results obtained from the first stage of the study were interesting. As it was clearly noticed the effect of the polymer on the sludge dewaterability and filterability. However for the centrifuge test, the different doses of the polymer had approximately the same dry solid content. The reason could be due to the long centrifugation time, high speed or the type of the polymer. Further explanation is provided below in section 5.3.

Another study was carried out with a more diluted solution of the two polymers and a shorter centrifuging time (5 and 15 minutes). A shorter time was used to study the effect of the centrifugation time on the obtained results from DS analysis and the SS analysis.

5.2 Second stage

For the second stage of the study, a more diluted solution of the polymers was prepared, which was 0.2%. The doses of the polymer used were 0.8, 1.6 and 3.3 g polymer/kg DS sludge. For the centrifuge part, a suspended solids analysis was carried out for the supernatant water and DS analysis for obtained sludge cake.

5.2.1 Polymer C-496

The following section shows the results obtained from the centrifuge test (5 and 15 minutes) and CST test when 0.2 % solution of polymer C-496 was used.

Centrifuge time 5 minutes

From Table 5.5 below, it can be noticed that the suspended solid content in the supernatant decreased with the polymer dose increment. For 3.3 g polymer/kg DS sludge had the smallest suspended solid content among the conditioned sludge samples. However, the no-polymer addition scenario had the lowest suspended solid content. As for the DS, a slight increment is noticed in the dry solid content with the polymer dose increment.

Table 5-5 The results obtained from different dose of the polymer C-496 and suspended solid content in the water phase and DS of the sludge cake for centrifuge test (5 minutes centrifuging time).

Polymer dose (g polymer/ kg DS sludge)	**Suspended Solid content in supernatant (mg/l) (Average ± standard deviation)**	**Dry solid content in cake % (Average ± standard deviation)**
0.0	1345.0 ± 234.0	9.0 ± 0.1
0.8	7347.0 ± 146.2	11.0 ± 0.5
1.6	5008.5 ± 208.5	9.7 ± 0.5
3.3	3062.0 ± 215.0	11.0 ± 0.2

Centrifuge time 15 minutes

From Table 5.6 below, it can be clearly seen that suspended solid content decreased with the polymer dose increment. For the dose 3.3 g polymer/kg DS sludge had the lowest suspended solid content among the conditioned sludge samples. For no polymer case, the suspended solid content in the supernatant was the lowest among the samples. The dry solid content had slightly increased with the polymer dose increment.

It can be seen that the results from 15 minutes centrifugation had slightly lower SS in the supernatant than 5 minutes centrifugation, which can be due to the longer centrifugation time.

Table 5-6 The results obtained from different dose of the polymer C-496 and suspended solid content in the water phase and DS of the sludge cake for centrifuge test (15 minutes centrifuging time).

Polymer dose (g polymer/ kg DS sludge)	**Suspended Solid content in supernatant (mg/l) (Average ± standard deviation)**	**Dry solid content in cake % (Average ± standard deviation)**
0.0	1905.5 ± 614.5	10.7 ± 0.1
0.8	6000.0 ± 0.0	11.0 ± 0.2
1.6	4117.0 ± 403.0	11.0 ± 0.2
3.3	3690.5 ± 168.4	11.0 ± 0.1

For both 5 and 15 minutes centrifuging time, the total suspended solids content values were high. The suspended solid content for the activated sludge is usually 2000-6000 mg/l (Hammer, 2014). Some obtained values from the centrifugation test were higher than 6000 mg/l. This could be resulted from the human mistake occurred during separating the supernatant and the solid phase, as the supernatant was collected by pouring the liquid in another beaker and later was taken for measuring the suspended solid content. Nevertheless, if the dewatering technique works properly a lower SS concentrations could be expected as the polymer dose increases (Dimitrova & Carlsson, 2011).

The supernatant obtained from the different dose of the polymer was muddy as shown in the attached picture in **Appendix B**.

CST

From Table 5.7 below, the unconditioned sludge had a very low filterability. The filterability increased with polymer addition. The CST was 100 seconds for 3.3 g polymer/ kg DS sludge.

Table 5-7 The results obtained from different dose of the polymer C-496 and average CST in seconds.

Polymer dose (g polymer/ kg DS sludge)	**Average of CST (seconds) (Average ± standard deviation)**
0.0	533.0 ± 47.1
0.8	416.7 ± 47.1
1.6	250.0 ± 40.8
3.3	100.0 ± 0.00

5.2.2 Polymer C-498

The following section shows the results obtained from the centrifuge test (5 and 15 minutes) and CST test when 0.2 % solution of polymer C-498 was used**.**

Centrifuge time 5 minutes

It can be noticed, from Table 5.8 that suspended solid in the water phase decreased regularly as the dose of the polymer increased. The dry solids content had slightly increased with the polymer dose increment. Furthermore, the suspended solids content was higher when sludge was conditioned with C-498 than C-496 in Table 5.5.

Table 5-8 The results obtained from different dose of the polymer C-498 and suspended solid content in the water phase and DS of the sludge cake for centrifuge test (5 minutes centrifuging time).

Polymer dose (g polymer/ kg DS sludge)	**Suspended Solid content in supernatant (mg/l) (Average ± standard deviation)**	**Dry solid content in cake % (Average ± standard deviation)**
0.0	1345.0 ± 234.0	9.0 ± 0.1
0.8	5570.0 ± 240.0	10.0 ± 0.4
1.6	5555.6 ± 0.0	10.6 ± 0.1
3.3	5000.0 ± 0.0	10.4 ± 0.1

Centrifuge time 15 minutes

From the Table 5.9 below, it can be seen that suspended solid content in the water phase was the highest at 1.6 g polymer /kg DS sludge, and lowest for 0.8 g polymer /kg DS sludge. However, the dry solids content had a slight increment with the polymer dose increment.

For the dose 0.8 g polymer/kg DS sludge had the lowest suspended solid content among the conditioned sludge samples. For no polymer case, the suspended solid content in the supernatant was the lowest among the samples.

It can be seen that the results from 15 minutes centrifugation had slightly lower SS in the supernatant than 5 minutes centrifugation, which can be due to the longer centrifugation time.

Table 5-9 The results obtained from different dose of the polymer C-498 and suspended solid content in the water phase and DS of the sludge cake for centrifuge test (15 minutes centrifuging time).

Polymer dose (g polymer/ kg DS sludge)	**Suspended Solid content in supernatant (mg/l) (Average ± standard deviation)**	**Dry solid content in cake % (Average ± standard deviation)**
0.0	1905.5 ± 614.5	11.7 ± 0.1
0.8	2778.0 ± 392.8	10.5 ± 0.3
1.6	5357.0 ± 0.0	11.4 ± 0.3
3.3	5000.0 ± 0.0	12.0 ± 0.2

CST

From Table 5.10 below, the CST for unconditioned sample was quite high and had shown a drop in the CST as the dose of polymer increased. However, the CST test results for C-496 shown in Table 5.7 were lower than CST results for C-498.

Table 5-10 The results obtained from different dose of the polymer C-498 and average CST in seconds.

Polymer dose (g polymer/ kg DS sludge)	**Average of CST (seconds) (Average ± standard deviation)**
0.0	533.0 ± 47.1
0.8	433.0 ± 62.4
1.6	366.7 ± 85.0
3.3	150.0 ± 40.8

5.3 Comparing the obtained results

The dose of the polymers were not determined based on a certain criteria. The aim was to investigate the effect of using different doses on the dry solid content of the sludge cake and the filterability. Furthermore, to investigate the effect of different centrifuging time on the suspended solids content and the dry solids content.

In the following sections, a comparison of the different centrifugation time and dose of polymer with the dry content (DS) and (SS) are presented.

Polymer C-496

From the Figure 5.2 below, it can be seen that the dose of the polymer was not affecting the dry solid content of the sludge cake when the centrifuge time was 30 minutes (approximately straight line). As the centrifuge time was changed, it can be noticed that a drier sludge cake was obtained.

In both 5 & 15 minutes results, the dry solids content continued to increase with the polymer dose addition. However, the DS for 30 minutes was the highest among the DS obtained from the three centrifugation times.

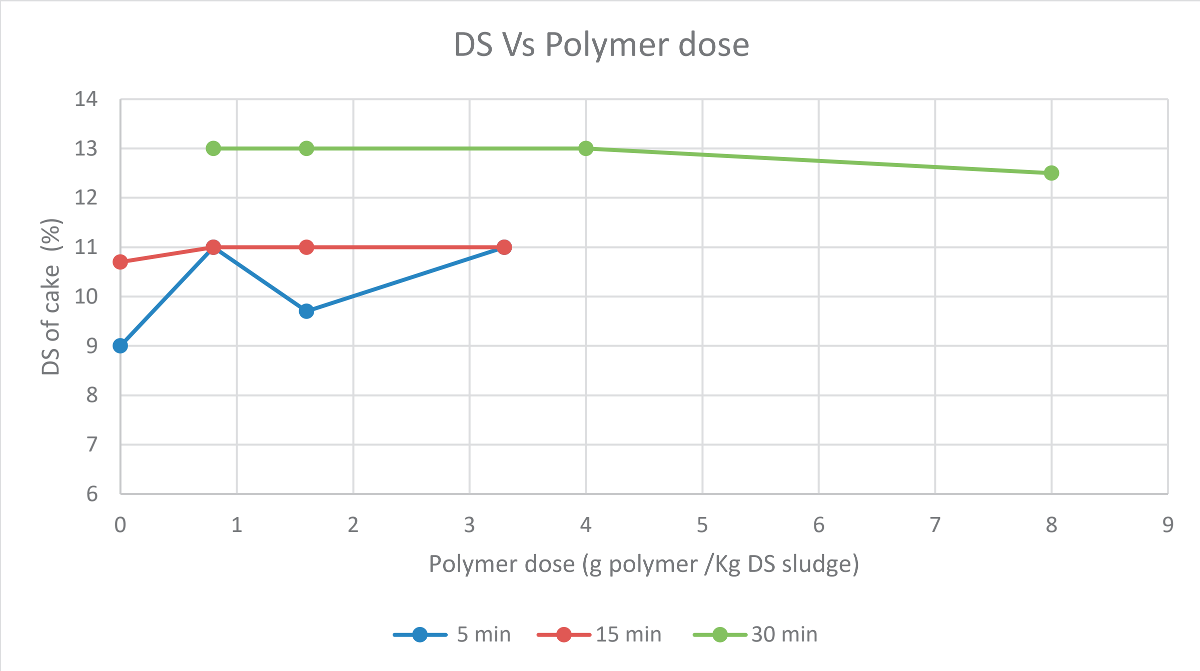

Figure 5.2 Different doses of the polymer C-496 and DS in sludge cake at different centrifuging times (5, 15 and 30 minutes)

Figure 5.3 below shows the variation of the SS for the supernatant water with the polymer dose for the two centrifuging time (5 & 15 minutes). The 15 minutes line showed lower SS than 5 minutes line for the 4 polymer dosage. The long centrifugation time could be the reason behind that, a larger supernatant volume was observed for the 15 minutes than for 5 minutes (Appendix C). The larger supernatant volume for the 15 minutes had a smaller SS content compared with the 5 minutes centrifugation results.

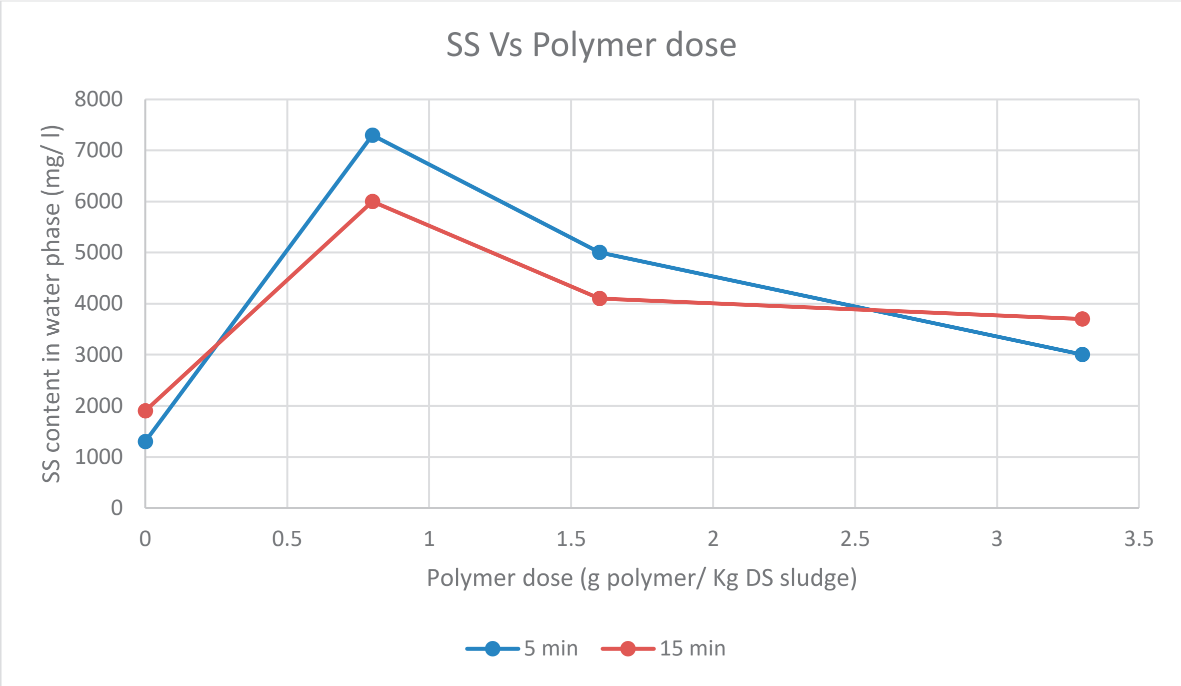

Figure 5.3 Different doses of the polymer C-496 and SS in sludge cake at different centrifuging times (5& 15 minutes)

Polymer C-498

In Figure 5.4 below, it can be noticed that similar pattern was noticed as for Polymer C-496 in Figure 5.2 . It can be seen that the dose of the polymer was not affecting the dry solid content of the sludge cake when the centrifuge time was 30 minutes (approximately straight line of 12.5%). As the centrifuge time was changed, it can be noticed a drier sludge cake was obtained. The sludge cake obtained from 15 minutes had a higher DS than cake obtained from 5 minutes centrifuging. However, the DS for 30 minutes was the highest among the DS obtained from the three-centrifugation time.

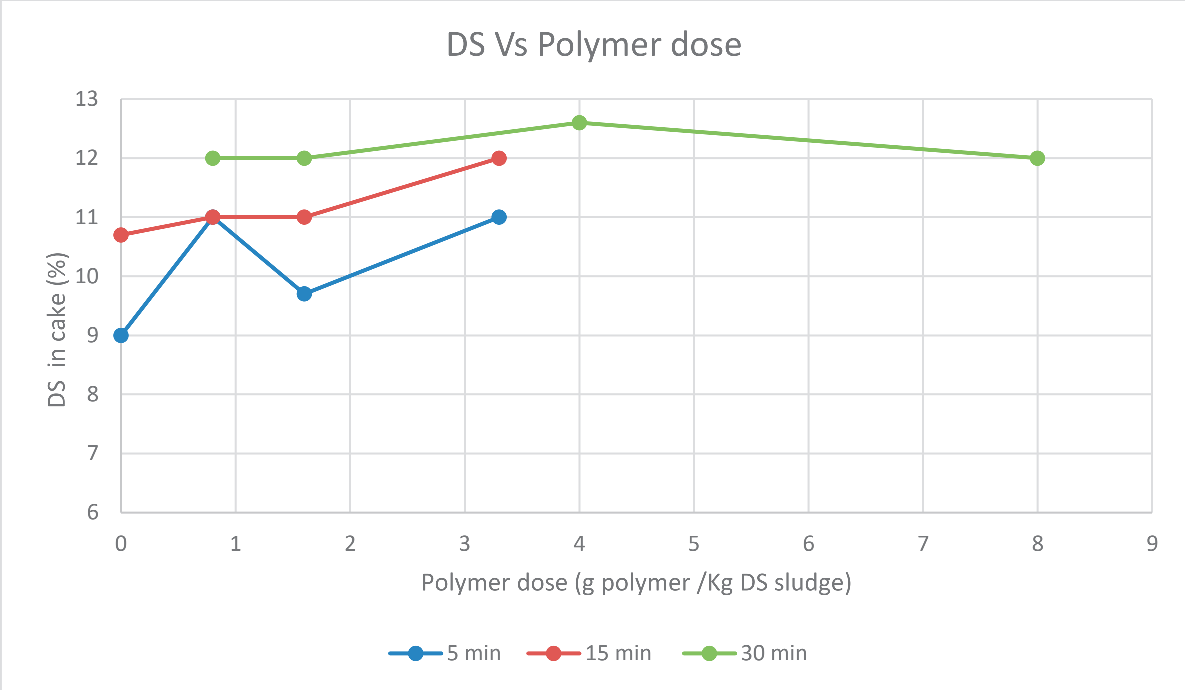

Figure 5.4 Different doses of the polymer C-498 and DS in sludge cake at different centrifuging times (5, 15 and 30 minutes)

The curves in Figure 5.5 represents a noticeable difference of suspended solid content with polymer dose addition. It can be noticed that the 15 minutes centrifugation obtained less SS in the supernatant water than results obtained from 5 minutes centrifugation. The difference could be due to the long centrifugation time.

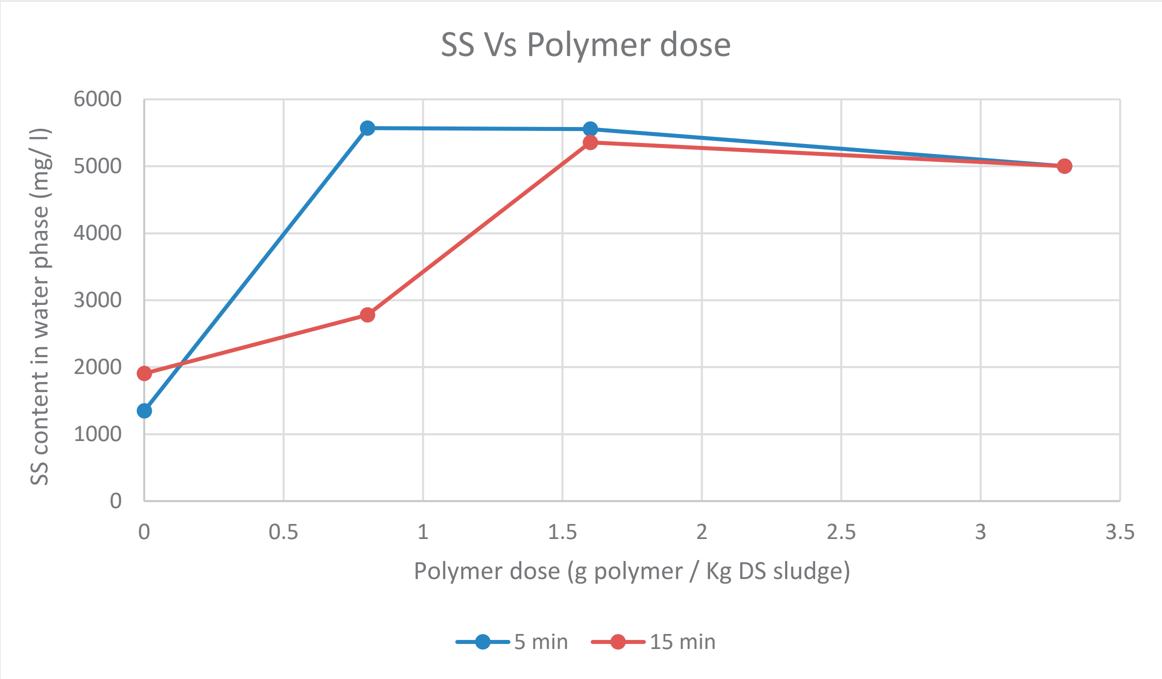

Figure 5.5 Different dose of the polymer C-498 and SS in sludge cake at different centrifuging times (5 & 15 minutes)

From the Figures (5.2, 5.3) (5.4, 5.5) above, it can be seen that the two polymers resulted in similar results. Furthermore, the different dose of the polymers did not give a large difference in DS of the sludge cake. The reason could be explained from studies carried out by Dentel (2001), Papavasilopoulos & Markantonatos (2001) and Hatziconstantinou & Efstathiou (2003). The three studies agreed that methods used for dewatering the sludge such as the centrifuge generates high shear, which leads to destruction of the sludge flocs. The reason behind sludge flocs destruction is using low shear resistant polymers to condition the sludge. The three studies concluded that for this kind of mechanical method the polymers type should preferably be more shear resistant.

Although different doses of the polymers were used, the results were approximately the same. This could be a result of having a relatively high molecular weight and high charge. A study carried out by Mamais *et al.,* (2006) investigated the behavior of polymers which have different molecular weight. The study showed a major difference in the obtained dry solid content when different doses of the polymer were used. Unlike the slight increment observed in this lab work.

High performance of centrifuge increases the sludge dryness. However, it is important to note that both the centrifuge intensity and centrifuge time are important factors to evaluate the performance of the centrifugation.

In this study, a G-force of 1613 was used for the three different times. The objective was to study the effect of using same intensity at different times (5, 15 and 30 minutes) on the sludge dewaterability. Nevertheless, from the obtained results it can be summarized that the centrifuge time did not have much effect on the cake dryness. The three different centrifuge durations have resulted in the same solid dry content percentage.

From the picture attached at **Appendix B** which shows the supernatant, it has a dark color. This could be a result of long centrifugation time which could have caused the flocs destruction and letting the fine particles to exit with the supernatant (SNF Floerger, N.d). As the speed (4000 rpm) was constant, further studies can be carried out by using different speed and study the effect of the speed on the centrifugation performance.

From a study carried out by (To *et al.*, 2016), a modified centrifugation was used. The resulted sludge cake in the lab had a dryness similar to the dry solid content on the large scale which was 30 %.

During the centrifugation test, a dry solid content of 12 % was obtained for the two polymers. Although on the large scale the solid content is around 20 – 25 %. The centrifuge high performance depends on both the intensity and the centrifuge time, some studies have proven that the intensity has more effect on the performance than the timing (SNF Floerger , N.d)

The centrifuge time at the beginning was set to 30 minutes but the obtained results displayed a dark supernatant. This could be resulted from the long centrifugation time which let the fine particles to exit with the supernatant as mentioned in SNF Floerger studies. Due to that, the centrifugation time was decreased to 5 and 15 minutes.

CST

From the two Figures 5.6 & 5.7, the effect of conditioning on the sludge filterability can be seen. As the dose of polymer was added more filterability was noticed in the sample (lower time).

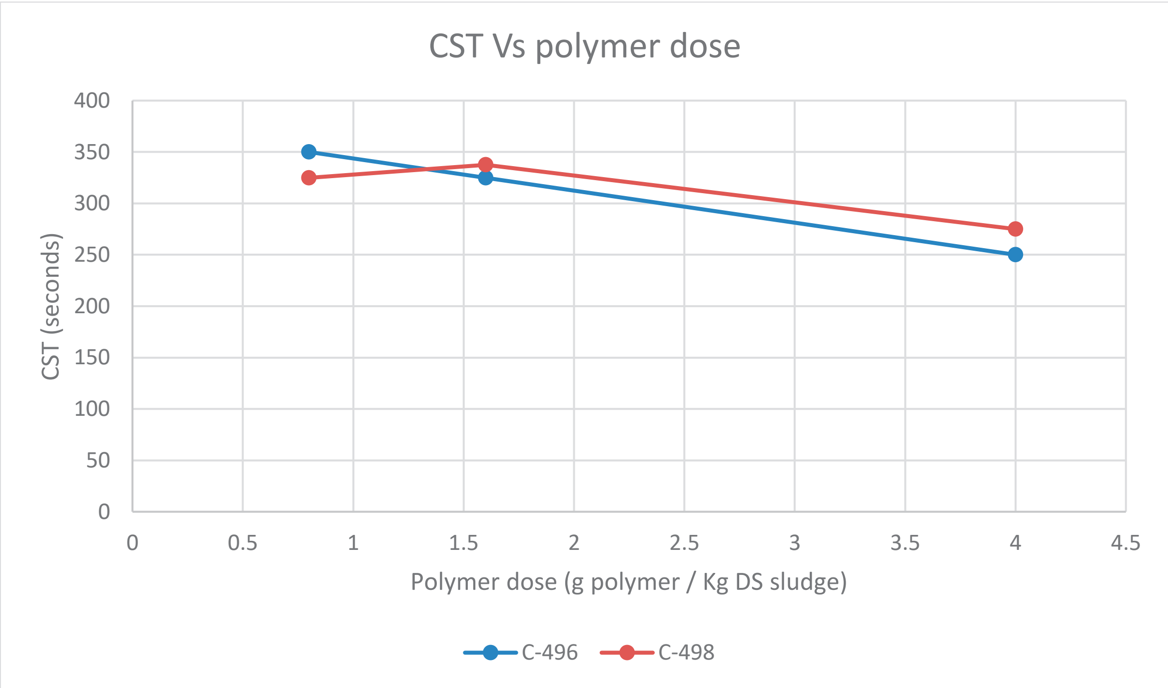

Figure 5.6 Different dose of the polymer C-496, C-498, and obtained CST (First stage)

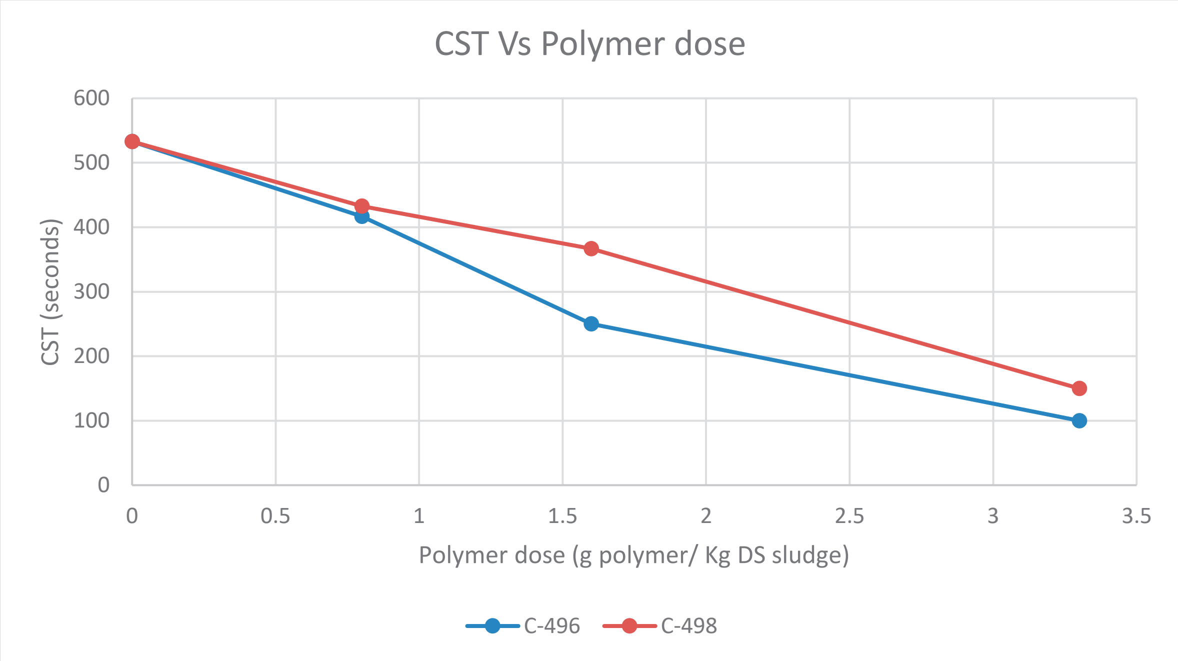

Figure 5.7 Different dose of the polymer C-496, C-498, and obtained CST (Second stage)

From the beginning of inventing the CST apparatus, the standard paper used for this test was Whatman NO.17 Chromatographic paper (Sawalha & Scholz, 2007). This paper is made of cellulose with a high flow rate of 190 mm per 30 min and with a mean pore diameter 8 μm. Sawalha & Scholz (2007) carried out research on assessing the CST test methodologies. During the research, different suction papers were used to evaluate the dewaterability of the sludge. However, relatively small differences (less than 2 seconds) were found when different suction paper were used. From the research, it can be stated that suction paper type does not have a major effect on the obtained results, as long as the suction paper is appropriate to execute the CST test.

It is important to notice that CST is not a sludge dewatering method, it provides information regarding the ease of separating the water portion from the solid portion in the sludge (Vesilind, 1988).

5.4 Evaluation of the lab work

Table 5.11 below shows the evaluation of the methods applied in lab work. The evaluation is based on different criteria: time required, space required , reliability of the results and simplicity. The time consumed for conditioning the sludge was the same for the three methods. However, the time calculated for the methods is the time used to execute the experiment, without including the time spent on conditioning the sludge. The three methods had a simple concept, but when applied on the lab some were simpler than the others.

Table 5-11 The evaluation of the methods applied in the lab

Method	Time required	Space required (equipment size)	Simplicity
CST	Less than 10 minutes.	0.044 m^2.	Very simple
Centrifuge	More than 24 hours.	0.42 m^2.	Simple
PFT	More than 24 hours.	0.0625 m^2.	Difficult

From the Table 5.11 above, the time consumed to execute the three methods was determined. The CST required the shortest time for method execution among the three methods. CST consumed only several minutes, depending on the sludge dewatering properties. Only 2 minutes were used to measure the sample and start the CST device. The test itself took not more than 8 minutes. The total time required for conducting the CST test until obtaining the results was 10 minutes.

The centrifugation test took more than 24 hours, which included the time used for conducting the actual work and time until the results were obtained. It took around 5 minutes to fill the centrifugation tubes with the sludge and set the centrifugation device on. The centrifugation time differed from 5, 15 and 30 minutes. After the centrifugation device stopped, it took about 30 minutes to measure the obtained supernatant volume and the sludge cake weight. Furthermore, it took around 100 minutes to carry out the SS analysis and 24 hours to obtain the results from DS analysis. The total time required for the centrifugation was 25.5 hours.

The total time required for pressure filtration test was not obtained, due to the occurrence of an incident in the lab. However, it could be estimated to be more than 24 hours, as DS analysis would be carried out on the obtained sludge cake.

The space requirement was convenient for the three method, the three methods required a space with in the laboratory room. The space depends on the device used to execute the experiment. The CST device has the smallest size among the three.

For the CST and centrifuge, each sample was triplicated. The reliability of the results could also be evaluated based on the calculated standard deviation as shown in the tables above. However, for some samples the standard deviation was relatively higher than others. From the calculated standard deviation for the sample, it can be noticed that standard deviation for SS analysis was high and was small for the DS analysis. The standard deviation for the CST test was high. The high standard deviation value due to the large difference between results obtained from the samples. The difference in the obtained results could be due to human error or inaccuracy of the device used.

Regarding the simplicity, CST test was the simplest and the results were obtained directly. The centrifuge is more complicated than CST test, because it required setting the time for centrifugation, speed and temperature. The results from the centrifugation test were not obtained directly as for the CST test. Based on the work in the laboratory, the PFT was considered difficult.

As for the centrifuge results, the dry solid (dry cake) content for all the samples were approximately around 12 % which is smaller than the large scale results which are around 20 -25 %. The supernatant phase suspended solid was around 2000 -6000 mg/l for most of the samples which is similar to the large scale results.

6 Conclusions and Recommendations

6.1 Conclusion

The thesis consisted of both literature reviewing and laboratory work. Seven methods for sludge dewatering in lab-scale were found from the literature reviewing. The methods are electro-dewatering, dewatering by osmosis, network strength, ultra-high-pressure filtration (UPF), capillary suction time (CST), centrifuge and lastly pressure filtration test. The last three method were conducted in the laboratory.

The methods found in the literature reviewing were evaluated based on the time required to execute the experiment and how comparable the obtained results to the large scale results. The ultra-high pressure method had a smaller dry solid content compared to the large scale results. Whereas, the other three methods obtained a similar dry solid content to the large scale result.

From the evaluation of the previous methods, the network strength method was more appealing. As the concept used in the network strength method gives more detailed information about the dewatering properties of the sludge than what the other methods provide. Furthermore, the results obtained from the small scale shared the same pattern as the results obtained from large scale.

As for the lab work, both CST and centrifuge test were conducted successfully. However, the pressure filtration test was not successfully executed due to some mechanical difficulties faced with the labox device. The labox device available in the lab had never been used before to filtrate sludge.

For both the CST and centrifuge, different doses of the polymer were used to condition the sludge. The main objective was to study the effect of the different sludge conditioning on the sludge dewaterability properties.

CST, Centrifuge and PFT used in the laboratory were evaluated according to how these methods were conducted through this study. The criteria used for evaluating the methods were the time required, space used in the laboratory, reliability of the results, and simplicity of conducting the experiments. The centrifuge results were compared with the large scale results. From the evaluation, CST is considered the easiest and the simplest. It only requires several minutes for executing and obtaining the results. On the other hand, centrifuge gives information about the obtained sludge cake and the supernatant. In addition, the SS analysis was carried out on the obtained supernatant and DS analysis on the obtained sludge cake.

To be concluded, several methods were found from the literature reviewing and two were conducted successfully in the laboratory. The different methods were evaluated based on certain criteria. The thesis goals were accomplished and further studies is recommended for a better understanding.

6.2 Recommendation

Different methods were interesting for the study, but due to the limitation of the time, some were not applied in the laboratory. Namely, the network strength method. Based on the results obtained from this study, it could be recommended that the following need further investigation.

- Different type of polymers

For this study, two similar polymers were used and both had approximately the same results. It would be interesting the study the effect of polymer conditioning on the dewaterability by using polymers with different molecular and charge weight.

- Dewatering methods executed in the laboratory.

The method found from the literature could be conducted on the laboratory, and furthermore evaluate the method based on the obtained results. Namely, the osmic dewatering and the net-work strength method.

- Centrifuge speed and time.

Only one speed for the centrifuge was set for the whole study period. The applied shear could have an obvious effect on the sludge dewaterability and how the separation between the solid and water phases is achieved.

- Another method of dewatering the sludge.

From the beginning of the lab work, it was planned to execute three method for the sludge de-watering. The pressure filtration (PFT) could be executed using another device.

- Polymer mixing with sludge.

The polymer was mixed with the sludge at a certain speed, which was 200 rpm for 2 minutes in this study; it would be interesting as well, if one could study the effect of mixing speed on the dewaterability properties of the sludge and the sludge floc structure.

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Appendix A

Instruments used in laboratory
Centrifuge (Centrifuge Sigma 3-16K)

The principle of the centrifuge Sigma 3-16K device is to install at least 4 samples in the centrifuge tubes. See Figure A.0.1 below. The method of the device is using the centrifuge force to separate the rejected water from solid sludge. The device have a wide range of values for the centrifuge time, radius and temperature. Both the temperature and the speed were constant for this study; however, the centrifuge timing had differed ranging from 5, 15 minutes to 30 minutes.

The speed of the centrifuge was set to 4000 rpm and the temperature at 25°C.
A sludge with no polymer addition was centrifuged for 5 minutes and 15 minutes. The sludge was conditioned at different polymer doses and centrifuged for 5, 15 and 30 minutes.
After the experiment, the supernatant water volume and the cake weight were measured. For the second stage of the experiment, the suspended solid of the rejected water was measured.

Figure A.0.1 The centrifuge Sigma 3-16K

CST (CST - Triton - W.P.R.L Type 92/1)
The capillary suction timer in Figure A.0.2 was used to measure the ability of the water to be sucked out from the sludge, which furthermore could represent the dewaterability of the sludge.

To conduct the experiment, the suction paper (Whatman NO. 1006-110) was placed over the base and covered by the detecting plate. The cylindrical metal was set in the middle of the detecting plate at the specified hole. The CST device was turned on by switching the power button on then the reset button was pressed once. After, the sludge was filled in the cylindrical metal; water was sucked out from the sludge by the suction paper beneath it.

The time needed for the water to go from the first circle to the second one was determined automatically. The device had a timer, which starts counting when front water touch the sensor. The timer stops when the water reaches the second senor.

The driving force for the CST test is suction force, which is considered larger than the hydrostatic pressure inside the cylinder. Based on this Scholz (2005) stated the irrelevancy of the sample volume to the CST performance, as long as the sample is enough to execute the experiment

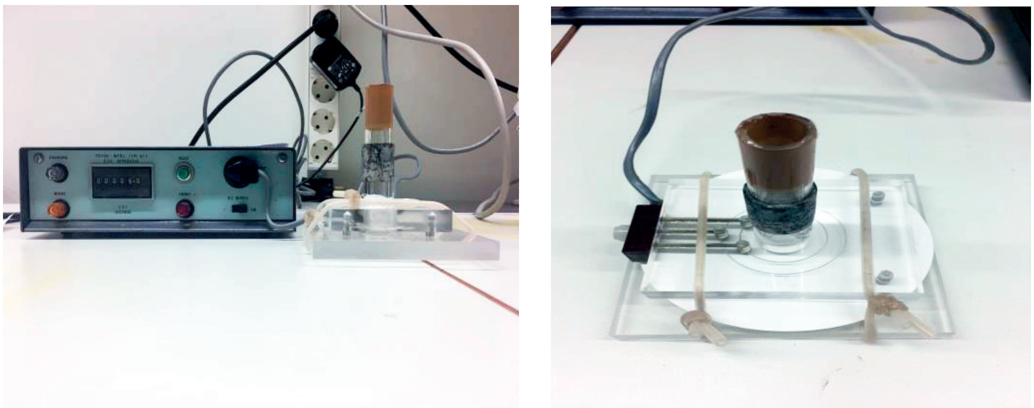


Figure A.0.2 Capillary suction time device (CST - Triton - W.P.R.L Type 92/1)

DS Analysis and SS Analysis (Oven - Binder)

The oven has a range of temperature as shown in the Figure A.0.3. For the entire study, the oven was set at 105°C to dry the water out from the sludge. Two analyses were conducted using the oven; the first one is the DS (Dry solid content from the sludge) for the sludge cake. The resulted cake sludge were kept in aluminum plates for 24 hours. The dry weight from this was used to calculate the DS for the sludge cake. The second analysis was the SS (suspended solids), which was carried out on the supernatant water.

A TS analysis was carried out on sludge on daily basic; to determine the polymer dose to the DS of sludge.

- The gravimetric method was used for the SS analysis based on Method 2540 D of *Standard Methods for Examination of Water and Wastewater, 23 rd Edition* (Baird *et al*., 2017).

Figure A.0.3 The oven used for this study

Scale (Sauter RE-1614 & Mettler PC 4400)

For weighing, scale were used as shown in the Figure A.0.4 below. The one on the left has four decimal digital accuracy, the unit was g. The scale on the right side showed up to two decimal digital accuracy and the unit was g. For weighing a certain subject, with the scale on the left side the container was situated at the central and weight was cleared to zero. The following step was filling the container with the subject and was scaled. The recorded weight on the screen was the net weight of the subject.

However, for the scale on the right side, the procedure was different as it was not possible to clear the scale to zero after placing the container. Therefore, a conventional procedure for calculating the weight was used to determine the weight of the subject. Which was weighing the container first and then weighing both the container and the subject together. The subject weight was obtained by subtracting the weights recorded earlier of (container and subject - weight of the container).

Figure A.0.4 The scales used for this study (left side: 4 decimal scale, right side 2 decimal scale)

Stirrer (Mix-drive 1 eco)

Magnetic was used for stirring, as shown in Figure A.0.5. The device has a variety of stirring speed ranging from 200 to 1200 rpm (rotation per minute). The magnetic rob inside the beaker interacted with the provided magnetic field. The stirrer was used to mix the polymer with the water during the preparing the polymer solution, and for mixing the polymer dose with the liquid sludge as well.

It is worth to mention that, the polymer solution for the both polymers (C-496 & C-498) were made by using the same steps. A new solution was made every day to be more accurate and eliminate any chance of polymer deterioration with the aeration. The polymer solution preparation is described below. To be mentioned, it was not known if the aeration plus the high speed stirring had affected the polymer structure or characterization.

Figure A.0.5 The stirrer used for this study

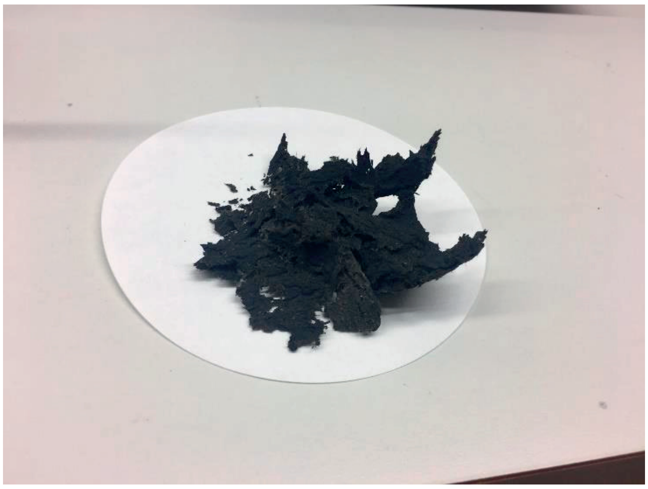
Other instruments

Another different instruments were used for this study as shown in Figure A.0.6. The plastic bucket was used for sludge sampling from full scale digester at Källby treatment plant. Cylinder was used to measure (100 ml) volume of water to prepare the polymer solution which was used for only one day. The shown beaker were used to mix the polymer agent with water, and for measure 300 g of liquid sludge followed by mixing the polymer with the sludge.

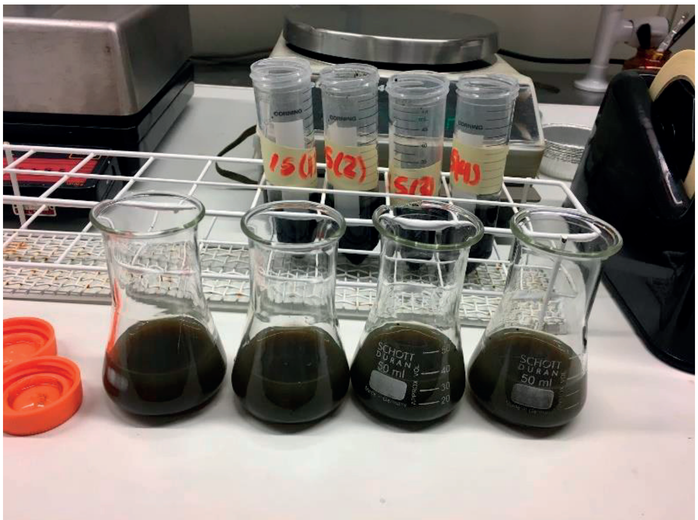
Both syringes the small and large ones(1ml & 10 ml) were used to measure the polymer dose. The small beakers were as well used to measure the weight of the rejected water, before carrying on with the suspended solid test. Both the spoon and squeezer were used to collect the sludge cake from the centrifuge tubes or while conducting the suspended solid test for the water phase in centrifuge tubes.

Figure A.0.6 Different tools used during the study

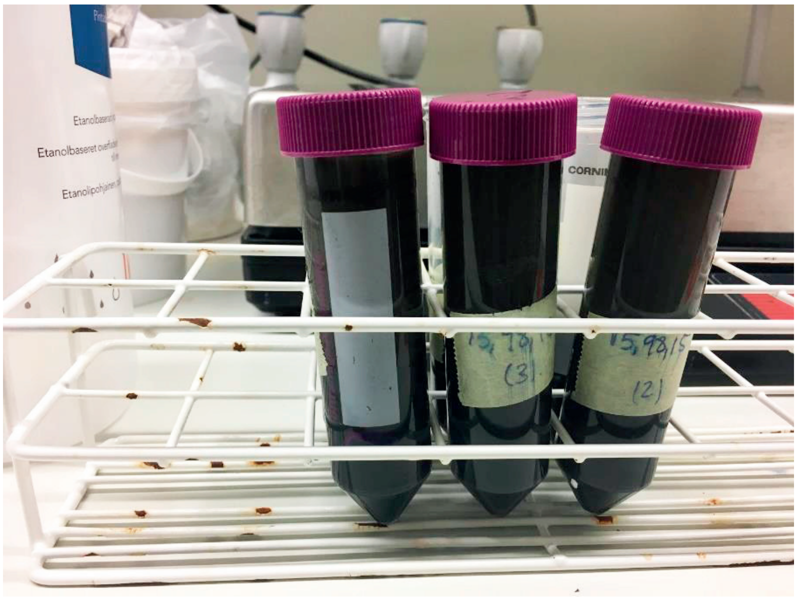
Appendix B



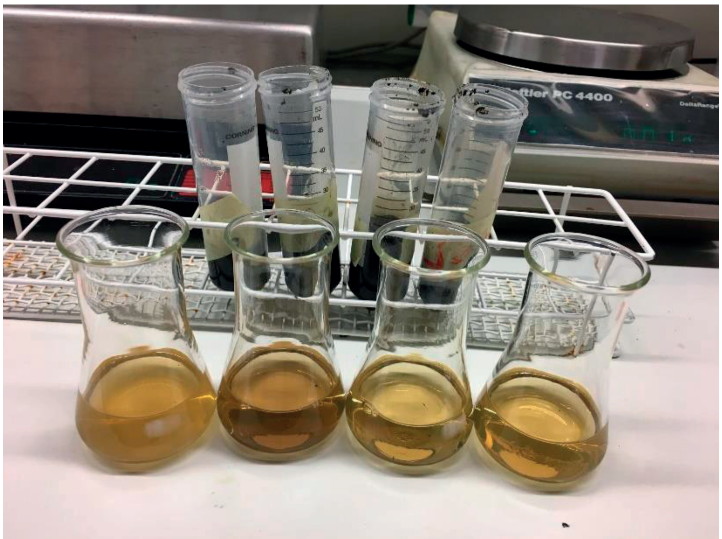
Above: obtained sludge cake after DS analysis.



Above: Water phase obtained from the centrifuge test (0.8, 1.6, 4 g polymer / DS of sludge) at first stage of the study.



Above: Samples after centrifuge test for 5 & 15 minutes for centrifuge test (0.8, 1.6, 3.3 g polymer / DS of sludge) at second stage of the study.



Above: Water phase obtained from the centrifuge test (8 g polymer / DS of sludge) at first stage of the study.

Appendix C : Lab work

Stage one of the study

Day 1 (4th April 2018)

Total Solid

Wet Weight(g)	Dry Weight (g)	Total Solid Content %
22.00	1.47	6.7
18.92	1.30	6.8
20.46	1.34	6.5
Average = 6.7 %		
Standard deviation = 0.1		

Polymer C-496

0.8 g polymer/ kg DS sludge

Wet Weight(g)	Dry Weight(g)	Dry Solid Content %
18.81	2.42	12.8
19.23	2.63	12.7
19.25	2.55	13.3
Average = 13.0 %		
Standard deviation = 0.2		

1.6 g polymer/ kg DS sludge

Wet Weight(g)	Dry Weight(g)	Dry Solid Content %
20.47	2.62	12.8
19.66	2.63	13.2
20.83	2.65	12.7
Average = 13.0 %		
Standard deviation= 0.2		

4 g polymer/ kg DS sludge

Wet Weight	Dry Weight	Dry Solid Content %
19.45	2.51	12.9
19.66	2.58	13.1
20.57	2.69	13.1
Average = 13.0 %		
Standard deviation = 0.1		

8 g polymer/ kg DS sludge

Wet Weight(g)	Dry Weight(g)	Dry Solid Content %
20.0	2.5	12.5
20.0	2.5	12.5
20.0	2.5	12.5
Average = 12.5 %		
Standard deviation=0.0		

CST

0.8 g polymer/ kg DS sludge

Experiment NO.	1	2	3	4
CST (seconds)	300.0	450.0	200.0	450.0
Average = 350.0				
Standard deviation= 106.1				

1.6 g polymer/ kg DS sludge

Experiment NO.	1	2	3	4
CST (seconds)	500.0	250.0	350.0	200.0
Average = 325.0				
Standard deviation= 114.6				

4 g polymer/ kg DS sludge

Experiment NO.	1	2	3	4
CST (seconds)	350.0	150.0	200.0	300.0
Average = 250.0				
Standard deviation= 79.1				

Day 2 (5 April 2018)

Polymer C-498

Total Solid content (TS %)

30 minutes

Wet Weight(g)	**Dry Weight(g)**	**Total Solid Content %**
17.91	2.75	6.6
20.80	1.32	6.4
17.84	1.17	6.6
Average = 6.5 %		
Standard deviation= 0.1		

0.8 g polymer/ kg DS sludge

Wet Weight(g)	**Dry Weight(g)**	**Dry Solid Content %**
22.43	2.75	12.3
19.92	2.46	12.4
20.47	2.57	12.3
Average = 12.0 %		
Standard deviation= 0.1		

1.6 g polymer/ kg DS sludge

Wet Weight(g)	**Dry Weight(g)**	**Dry Solid Content %**
21.45	2.69	12.5
19.90	2.59	13.0
20.27	2.49	12.3
Average = 12.5 %		
Standard deviation= 0.3		

4 g polymer/ kg DS sludge

Wet Weight	Dry Weight	Dry Solid Content %
19.68	2.57	13.1
20.95	2.58	12.3
21.63	2.69	12.4
Average = 12.6 %		
Standard deviation= 0.3		

8 g polymer/ kg DS sludge

Wet Weight(g)	Dry Weight(g)	Dry Solid Content %
21.52	2.69	12.5
21.61	2.56	11.8
20.52	2.50	12.1
Average = 12.0 %		
Standard deviation= 0.3		

CST

0.8 g polymer/ kg DS sludge

Experiment NO.	1	2	3	4
CST (seconds)	350.0	300.0	150.0	500.0
Average = 325.0				
Standard deviation= 125.0				

1.6 g polymer/ kg DS sludge

Experiment NO.	1	2	3	4
CST (seconds)	250.0	200.0	700.0	200.0
Average = 337.5				
Standard deviation= 210.3				

4 g polymer/ kg DS sludge

Experiment NO.	1	2	3	4
CST (seconds)	150.0	350.0	300.0	300.0
Average = 275.0				
Standard deviation= 75.0				

Second stage of study

Day 1 (7 may 2018)

No polymer

Total solids:

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
24.51	1.43	5.8
26.76	1.57	5.8
26.49	1.61	6.1
Average = 6.0 %		
Standard deviation= 0.1		

Centrifuge for 5 min:
Suspended solids SS

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
19.0	0.15	0.12	1579.0
18.0	0.14	0.12	1111.1
Average = 1345.0			
Standard deviation= 234.0			

Solid phase:

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
30.0	2.7	8.8
28.8	2.6	9.1
28.8	2.6	8.9
Average = 9.0 %		
Standard deviation= 0.1		

Centrifuge for 15 minutes:

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
22.0	0.18	0.12	2727.3
23.0	0.16	0.12	1739.1
24.0	0.15	0.12	1250.0
Average = 1905.5			
Standard deviation= 614.5			

Solid phase:

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
27.66	2.95	10.7
24.66	2.64	10.7
24.96	2.69	10.8
Average = 10.7%		
Standard deviation= 0.1		

CST:

Experiment NO.	1	2	3
CST (seconds)	500.0	500.0	600.0
Average = 533.0			
Standard deviation= 47.1			

Day 2 (8 May 2018)
Polymer C-496
1.6 g polymer /kg DS sludge

TS:-

Wet Weight (gram)	**Dry Weight (gram)**	**Total Solid Content %**
23.65	1.43	6.0
27.06	1.55	5.7
29.12	1.71	5.8
Average = 5.8%		
Standard deviation= 0.1		

Centrifuge for 5 min:

Volume of supernatant (ml)	**Final weight (g)**	**Original weight of filter (g)**	**Total suspended Solid Content (mg/l)**
25.0	0.24	0.12	4800.0
23.0	0.24	0.12	5217.0
Average = 5008.5			
Standard deviation= 208.5			

Solid phase:

Wet Weight (gram)	**Dry Weight (gram)**	**Total Solid Content %**
22.32	2.33	10.4
25.67	2.42	9.4
28.15	2.66	9.4
Average = 9.7%		
Standard deviation= 0.5		

Centrifuge 15 min:
SS:

Volume of supernatant (ml)	**Final weight (g)**	**Original weight of filter (g)**	**Total suspended Solid Content (mg/l)**
25.0	0.21	0.12	3600.0
19.0	0.22	0.12	4166.7
24.0	0.23	0.12	4583.3
Average = 4117.0			
Standard deviation= 403.0			

Solid phase:

Wet Weight (gram)	**Dry Weight (gram)**	**Total Solid Content %**
24.59	2.68	10.8
24.77	2.68	10.6
18.72	2.08	11.1
Average = 11.0 %		
Standard deviation= 0.2		

3.3 g polymer /kg DS sludge
Centrifuge for 5 minutes:
SS:

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
29.0	0.20	0.12	2758.6
28.0	0.21	0.12	3214.3
28.0	0.22	0.12	3214.4
Average = 3062.0			
Standard deviation= 215.0			

Solid phase:

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
20.14	2.18	10.8
22.46	2.44	10.8
23.46	2.44	10.5
Average = 11.0 %		
Standard deviation= 0.2		

Centrifuge for 15 min:
SS:

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
28.0	0.22	0.12	3571.4
28.0	0.23	0.12	3928.6
28.0	0.22	0.12	3571.4
Average = 3690.5			
Standard deviation= 168.4			

Solid phase:

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
22.45	2.59	11.5
22.93	2.59	11.3
23.26	2.61	11.2
Average = 11.0 %		
Standard deviation= 0.1		

Day 3 (9 May 2018)
TS %

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
21.61	1.28	5.9
17.33	1.07	6.2
22.53	1.38	6.1
Average = 6.1 %		
Standard deviation= 0.1		

Polymer C-496
O.8 g polymer / kg DS sludge
Centrifuge for 5 min:
SS:

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
20.0	0.25	0.12	7150.0
20.0	0.27	0.12	7500.0
23.0	0.29	0.12	7391.0
Average = 7347.0			
Standard deviation= 146.2			

Solid phase:

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
24.37	2.54	10.4
29.3	2.7	9.2
27.22	2.63	9.7
Average = 11.0 %		
Standard deviation= 0.5		

Centrifuge for 15 min:
SS:

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
25.0	0.27	0.12	6000.0
25.0	0.27	0.12	6000.0
25.0	0.27	0.12	6000.0
Average = 6000.0			
Standard deviation= 0.0			

Solid phase:

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
25.57	2.84	11.1
25.82	2.78	10.8
Average =11.0 %		
Standard deviation= 0.2		

Polymer-C-498:
O.8 g polymer / kg DS sludge
Centrifuge for 5 minutes
SS:

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
22.0	0.25	0.12	5909.0
26.0	0.26	0.12	5384.6
24.0	0.25	0.12	5416.7
Average = 5570.0			
Standard deviation= 240.0			

Solid phase:

Wet Weight (gram)	**Dry Weight (gram)**	**Total Solid Content %**
28.95	2.72	9.4
27.09	2.69	10.0
25.27	2.63	10.4
Average = 10.0 %		
Standard deviation= 0.4		

Centrifuge of 15 min:
SS:

Volume of supernatant (ml)	**Final weight (g)**	**Original weight of filter (g)**	**Total suspended Solid Content (mg/l)**
24.0	0.18	0.12	2500.0
24.0	0.18	0.12	2500.0
24.0	0.24	0.12	3333.3
Average = 2778.0			
Standard deviation= 392.8			

Solid phase:

Wet Weight (gram)	**Dry Weight (gram)**	**Total Solid Content %**
25.54	2.63	10.7
27.0	2.72	10.0
19.2	2.06	10.7
Average = 10.5%		
Standard deviation= 0.3		

1.6 g polymer / kg DS sludge
Centrifuge 5 min:

Volume of supernatant (ml)	**Final weight (g)**	**Original weight of filter (g)**	**Total suspended Solid Content (mg/l)**
27.0	0.27	0.12	5555.6
27.0	0.27	0.12	5555.6
27.0	0.27	0.12	5555.6
Average = 5555.6			
Standard deviation= 0.0			

Solid phase:

Wet Weight (gram)	**Dry Weight (gram)**	**Total Solid Content %**
25.3	2.67	10.6
24.4	2.62	10.7
25.0	2.65	10.6
Average =10.6%		
Standard deviation= 0.1		

Centrifuge of 15 min:
SS:

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
28.0	0.27	0.12	5357.0
28.0	0.27	0.12	5357.0
28.0	0.27	0.12	5357.0
Average = 5357.0			
Standard deviation= 0.0			

Solid phase:

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
21.81	2.57	11.8
22.83	2.61	11.4
24.32	2.69	11.0
Average = 11.4 %		
Standard deviation= 0.3		

3.3 g polymer / kg DS sludge
Centrifuge of 5 minutes:
SS:

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
28.0	0.26	0.12	5000.0
28.0	0.26	0.12	5000.0
28.0	0.26	0.12	5000.0
Average = 5000.0			
Standard deviation= 0.0			

Solid phase

Wet Weight (gram)	Dry Weight (gram)	Total Solid Content %
23.83	2.5	10.5
23.4	2.4	10.3
24.2	2.5	10.3
Average =10.4 %		
Standard deviation= 0.1		

Centrifuge of 15 min:
SS:

Volume of supernatant (ml)	Final weight (g)	Original weight of filter (g)	Total suspended Solid Content (mg/l)
28.0	0.26	0.12	5000.0
28.0	0.26	0.12	5000.0
28.0	0.26	0.12	5000.0
Average = 5000.0			
Standard deviation= 0.0			

Solid phase:

Wet Weight (gram)	**Dry Weight (gram)**	**Total Solid Content %**
19.89	2.43	12.2
20.57	2.44	11.8
21.6	2.62	12.1
Average =12.0 %		
Standard deviation= 0.2		

Day 4 (11 May 2018)

Capacity Suction Time:

TS:

Wet Weight (gram)	**Dry Weight (gram)**	**Total Solid Content %**
14.34	0.74	5.2
21.89	1.13	5.2
14.58	0.74	5.1
Average = 5.2 %		
Standard deviation= 0.1		

Polymer C-496:

O.8 g polymer / kg DS sludge

Experiment no.	1	2	3
CST (seconds)	350.0	450.0	450.0
Average= 416.7			
Standard deviation= 47.1			

1.6 g polymer / kg DS sludge

Experiment no.	1	2	3
CST (seconds)	250.0	200.0	300.0
Average = 250.0			
Standard deviation= 40.8			

3.3 g polymer / kg DS sludge

Experiment no.	1	2	3
CST (seconds)	100.0	100.0	100.0
Average= 100.0			
Standard deviation= 0.0			

Polymer C-498:

O.8 g polymer / kg DS sludge

Experiment no.	1	2	3
CST (seconds)	500.0	450.0	350.0
Average= 433.3			
Standard deviation= 62.4			

1.6 g polymer / kg DS sludge

Experiment no.	1	2	3
CST (seconds)	450.0	250.0	400.0
Average= 366.7			
Standard deviation= 85.0			

3.3 g polymer / kg DS sludge

Experiment no.	1	2	3
CST (seconds)	100.0	150.0	200.01
Average= 150.00			
Standard deviation= 40.8			

Appendix D : Popular Scientific Summary

Why to dewater our sludge?

Wastewater is collected from different household then channeled to the treatment plant where it goes through physical, biological and chemical treatment. Then a by-product is produced from these different process called sludge, which requires further treatment before final disposal.

The sludge undergoes thickening, conditioning and dewatering processes before the final disposal. In the thickening stage, the solids of the sludge are concentrated and the water volume is reduced. The conditioning phase is a process of breaking out the jelly-like layer in the sludge by using chemicals (polymers) or various means. The following step is the dewatering of the sludge.

Sludge dewatering is basically separating the solid and liquid components to minimize the waste. It is important to note that sludge dewatering does not treat the sludge, it only separate the two states for further separate treatment and easier final disposal. Besides that, reducing the volume of sludge corresponds to a reduction of transportation and final disposal costs.

Different technologies are used nowadays for sludge dewatering but to maximize and increase the dewatering efficiency, it is imperative to have more researches studying the composed sludge dewatering properties and evaluate the used method in a small scale. Furthermore, compare this used methods with the results obtained from large scale.

The methodology used for this work are both literature reviewing and conducted experiments in the laboratory. From the literature reviewing, four methods were found which are Electro-dewatering, Osmosis pressure for dewatering, Ultra high pressure and Network strength methods. These methods were then evaluated using different criteria : the time used to conduct the experiment and how comparable the obtained results with the full scale results. The evaluation was based on the available data found in the scientific reports of these methods.

The laboratory work consisted of conducting three methods which are Capillary Suction Time (CST), Centrifuge and Pressure filtration test (PFT). The Capillary suction time method is not a sludge dewatering method but it provides information regarding the ease of separating the water portion from the solid one in the sludge. The Centrifuge performance on the other hand depends on different parameters; intensity, time, type of sludge and the used polymer. The pressure filtration test (PFT) principle is applying pressure on the sludge sample to extract the water from the sludge.

The capillary suction time was measured for the different doses for the two polymers type. As for the centrifuge, different time durations were used with a constant speed to study the effect of the centrifugation timing on the sludge dewaterability. The method were then evaluated based on simplicity of implementation, time required to conduct the experiment, area used in the laboratory and how comparable the results are to the large scale results.

The results and conclusions achieved in this study are tangible proof and indicator to conduct more research in this area. A better understanding of this will lead to improve the way we handle the sludge today and the waste management.