Municipal wastewater sludge dewaterability using bench-scale units

by

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DECLARATION

I, Megan Jade Abrahams, declare that the contents of this dissertation/thesis represent my unaided work and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Megan Abrahams July 2020

Signed **Date**

Cape Peninsula University of Technology

Abstract

The sludge produced by municipal wastewater treatment plants (MWWTPs) amounts to a small percentage by volume of the processed wastewater. However, it is handling accounts for approximately 50% of the total operating cost. Minimisation of bio-solids is critical in the wastewater treatment industry, but there are challenges in predicting dewatering performance. The dewatering performance can be overcome by optimising the sludge treatment process, especially conditioning. Sewage sludge is highly complex by nature and possesses unpredictable behaviour, due to the change in the composition of the raw inflow to the wastewater treatment works, hourly, daily, monthly, seasonally. Currently, there is a void in reliable bench-scale methodology and data to dewatering efficiency. This research study aimed to investigate sludge dewaterability at four MWWTPs using a gravity drainage test unit as well as a bench-scale press.

The following observations were noted. Both experimental tests were able to predict sludge dewaterability, in terms of filtration using gravity drainage, cake height and cake moisture content. The volatile suspended solids (VSS) was found to be the most influential sludge characteristic. This was due to a relationship existing between cake dryness and the VSS. For a lower VSS of 3230 mg/l, a cake dryness of 18% was found, and for a higher VSS of 7162 mg/l, a cake dryness of 13 % was obtained.

The experimental work also showed that polymer demand is dependent on feed solids % of the sludge. WWTP D with the highest feed solids, 3.14 %, required more polymer for flocculation to be established, at a minimum polymer demand of 30 ml. Whereas, WWTP A with the lowest feed solids of 1.87 % only required 12 ml of minimum polymer demand to establish flocculation. The alkalinity parameter for the treated effluents used was the only out of spec parameter that possibly interfered with the strength of polymer solution made-up. Treated effluent after filtration yielded a higher alkalinity value of 333 mg/l $CaCO_3$. Therefore, during the gravity drainage experiment, the polymer solution made-up with treated effluent after filtration yielded the least amount of filtration in most of these experiments. The MBR treated effluent used as the solvent, gave to lowest polymer demand.

The assessment of the dewaterability of sludge dewatering mathematically, the Specific Resistance to Filtration (SRF) on polymer dosage was obtained for the two polymers used, FLOPAM 4650 and FLOPAM 4800. It was found that SRF decreased with an increase in polymer dosage for both polymers used. For the bench press experiment, a direct correlation between sludge cake height and moisture content was observed. An increase in cake height increased the amount of solids in the cake. The Box Behnken Design model fitted the data and proved that a relationship existed between polymer dosage, cake solids concentration, and cake height during the bench-scale press tests.

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Dedication

My parents and role models, for their endless love, support, and inspiration;
This achievement would not have been possible without you

Thank You!

Research Outputs

M. Abrahams, M. Aziz and T Ojumu**;** The investigation of different cationic charge polymers for Municipal Wastewater sludge dewater-ability, CPUT Annual Post Graduate Conference, SARETEC, Cape Town, South Africa, 7 November 2018

M. Abrahams, G Kasongo, T Ojumu, and M. Aziz**;** The investigation of different cationic charge polymers for Municipal Wastewater sludge dewater-ability, *IWA Water Practice & Technology*, submitted December 2019.

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Parameters	Description	Unit
A	Filtration area	m^2
b	The slope of a straight line	
C	Suspended solids concentration	kg/m^3
g	Gravitational constant	m/s^2
h	Height of the sludge volume before experimental tests	cm
P	Vacuum pressure	Pa
p_1	Liquid pressure	Pa
q	Liquid flux	m/s
R_M	The initial resistance of filter medium	
r	Specific resistance to filtration	m/kg
t	Time	s
V	Volume of filtrate	m^3
Greek Symbols		
α	Local specific resistance	m/kg
μ	Liquid viscosity	Pa.s
ω	Position in the cake in the form of the number of solids deposited per unit cross-section area	kg/m^2

List of Abbreviations

ANOVA	Analysis of variance
BBD	Box-Behnken Design
DAF	Dissolved air flotation
DS	Dry Solids
DSVI	Dissolved sludge volume index
EPS	Extracellular polymeric substances
FS	Feed solids
MBR	Membrane bioreactor
ML	Mixed Liquor
MSWWTW	Municipal sewage wastewater treatment works
OPD	Optimum polymer dosage
PD	Polymer Demand
RAS	Returned Activated Sludge
SRF	Specific resistance to filter
SS	Suspended Solids
SVI	Sludge volume index
TSS	Total Suspended solids
TS	Total Solids
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WWTP	Wastewater treatment plant

Chapter 1

INTRODUCTION

1.1 Background

Biological sludge tends to form highly compressible cakes, and the sludge properties change continuously. These bio-sludges must be dewatered adequately before disposal. It contains a large number of fine particles, as well as high water content, which formulates its highly compressible nature, making it challenging to dewater. (Chen, 2013). The high-water content found in sewage sludge is responsible for its large volumes produced, which prevents the sludge from being processed, such as in landfilling or incineration. Due to the high cost of transportation, incineration and drying energy would increase tremendously (Dominiak *et al*., 2011).

Due to the highly compressible nature of sludge, pre-treatment is required before dewatering to enhance the removal of water during the dewatering process. The most commonly used pre-treatment method is chemical treatment using charged organic polymers, also referred to as polyelectrolytes. Which is then followed by the dewatering step mainly performed by mechanical techniques based on centrifugation or filtration, e.g., by belt or filter press (Chen, 2013).

1.2 Sludge characteristics affecting sludge dewatering

Several sludge characteristics are known to influence its ability to dewater. These sludge characteristics are extracellular polymeric substances (EPS), suspended solids concentration, optimal polymer dose, viscosity, hydrophobicity, physiological and physicochemical effects, mono- and divalent cations, COD/Phosphorus ratio, pH, and surface charge (Saveyn *et al*., 2005). It also must be noted that activated sludge composition may change over time as a result of either changing wastewater composition or concentration, changing environmental parameters, such as temperature, or changing process parameters, such as sludge residence time (Saveyn *et al*., 2005). Other than sludge characteristics, polyelectrolyte characteristics also play an essential role in the dewatering performance. These characteristics include average molecular weight and charge density or cationic (Saveyn *et al*., 2005).

Many factors influence the dewaterability of sludge, as mentioned above; therefore, tests should be conducted daily. This can will be achieved by obtaining a standard method to evaluate sludges dewaterability. According to Freese et al. (2004), the primary methods used to measure sludge dewaterability are capillary suction time (CST), and specific resistance to filter (SRF), as well as, the moisture content of the dewatered sludge, of which 15-25 % is attainable (Lu *et al*., 2012).

Lab-scale methods such as filtration-compression cell tests (Chen, 2013), piston-driven cylindrical filter press (Saveyn et al., 2005), as well as UV- spectrophotometer (DiMassimo et al., 2015) are a few of the successful tests used to analyse the dewatering performance. However, many lab-scale tests are not successful when applied to the industrial scale. This could be due to the difference in the size of the lab-scale as compared to the industrial scale. The impact the size difference has of sludge dewatering was proven by researcher Chen (2013), for his filtration-compression test on lab-scale. The outcome was that "Laboratory pressure filtration can show general trends of the dewatering behaviour but cannot match plant-scale operation due to dissimilarities in the equipment configuration and operating procedures" (Chen, 2013). Therefore, a knowledge gap exists in the sludge dewatering process, and further investigation of the existing as well as newer methods will be evaluated.

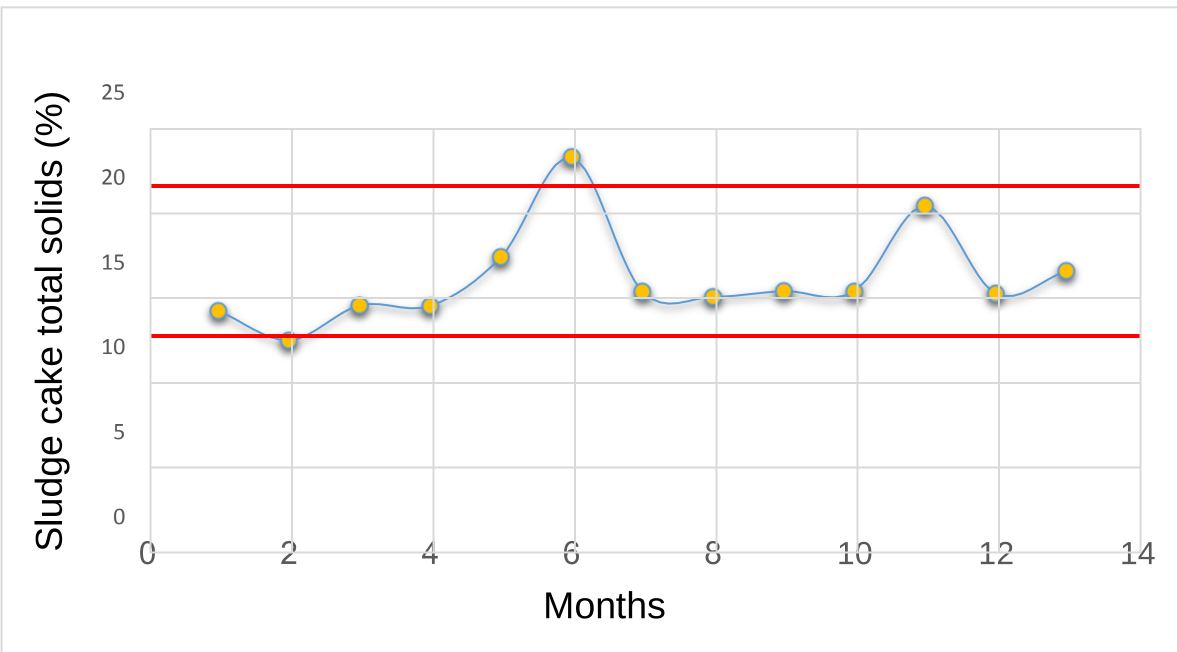


Figure 1.1: Sludge cake total solids after sludge dewatering by belt filter press

Figure 1.1 represents the historical data for moisture content test results of dewatered sludge cake produced at a WWTP of the City of Cape Town. The design limits for the solids concentration % for waste activated sludge (WAS), according to Lu *et al.,* 2012 is 15 – 25 % attainable via belt filter press. In Figure 1.1, the design limit was only achieved thrice within 14 months, at months, 5 (15%), 6 (22%), and 11 (18%).

Another sludge dewatering influencing parameter investigated for this research study is polymer consumption. Which is required polymer (kg) needed to dewater one dry ton of sludge.

The required polymer consumption, according to SNF Floerger, a company currently responsible for the screening, troubleshooting, and optimisation tests for sludge dewatering applications within the City of Cape Town, of waste activated sludge (WAS) should be 3.5 kg/DTS to 5 kg/DTS. Figure 1.2 below represents the polymer consumption for WWTP B over five years. This Figure shows how inconsistent polymer consumption is for the majority of the data points, due to no reliable bench-scale method available to check on an hourly basis, daily or monthly. Therefore not being able to troubleshoot or optimise the sludge dewatering operation.

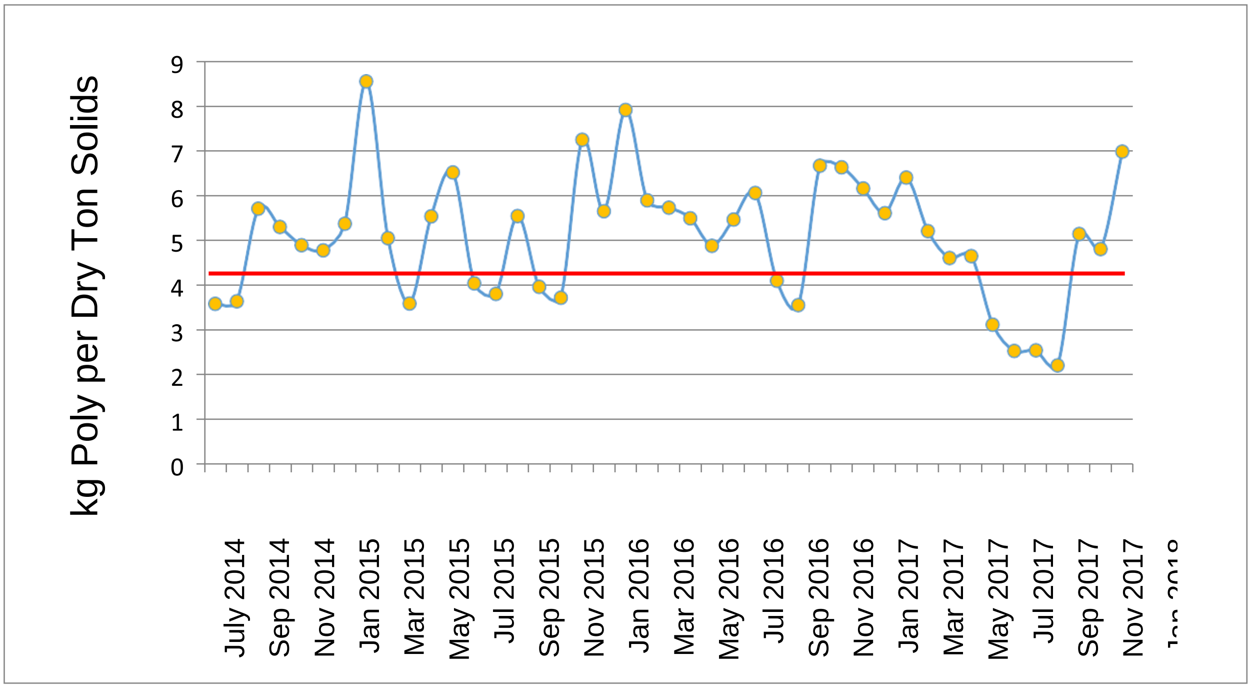


Figure1.2: Polymer consumption

Another method used to justify the problem was a verbal survey conducted with all WWTW plant managers. The outcome of this survey proved that most dewatering facilities within the City of Cape Town have no reliable method to assess their dewatering operation. Out of the 29 WWTW within the City of Cape Town, only 10 has belt filter presses, and out of the 10 WWTWs, only 3 of those plants check on the dewaterability daily. As stated previously, dewatering is an expensive process, and the polymer consumption, moisture content, as well as belt filter press performance, are essential focus points to assess the sludge dewatering operation. Therefore, a standard method is needed to optimise the existing dewatering plants as well as for the future WWTPs.

1.3 Research Problem

During the conventional activated sludge process, various municipal sewage wastewater treatment works (MWWTWs) in the City of Cape Town (CoCT), a large amount of waste activated sludge is generated for processing in the dewatering facilities. In 2014 a waste quantity of 8 212 496 tons of waste in the Western Cape was generated, with the City of Cape Town generating more than 60% of this total (Vice *et al*., 2014). The bio-solid cake produced during the dewatering processes is characterised by a low solid content, which is below the expected levels of 15 – 25 % stipulated by Lu *et al*., 2012.

1.4 Research Topic

A thorough investigation regarding the use of standard methods for assessing sludge dewatering, let to needing to obtain a viable method. The method used needs to be practical with the ability to be used daily by semi-skilled workers, also for the conditioning of a new dewatering facility. Lastly, when the optimisation of a dewatering facility is required, the standard method should be used to assist in this regard. Since there is no practical evaluation of the dewatering facility within the CoCT, the significant sections of the process will be of focus. Gravity drainage and compression are the utmost essential steps within the belt filter press operation and will be dealt with separately in these lab-scale experiments. The measurable parameters of focus will be polymer concentration, cake moisture content, cake height, gravity drainage volume, and gravity drainage time.

1.5 Research question

How do sludge characteristics, with the use of treated effluent as polymer dilution water; and change in polymer concentration, affect the drainability and compressibility of four MWWTWs waste activated sludge's?

1.6 Aim of the research

This study aims to evaluate the effects of sludge characteristics and flocculant concentration on dewatering, and to provide an experimental method that measures sludge drainability used to assess belt filter press operations. By the end of these experiments, the aim is to obtain a standard method with reliable data and information regarding the sludge dewatering facilities.

1.7 Objectives:

To evaluate dewatering based on:

- Characteristics of four different wastewater sludge's
- Two types of flocculants at two concentrations levels
- Gravity drainage test to obtain highest drained filtrate volume in the shortest time
- Feed solid concentration using a bench press

1.8 Significance of the research

It was understanding the sludge characteristics and polymer consumption and its influence on sludge dewatering. This knowledge will be applied to effectively measure and control the dewatering operation to save on costs. To obtain a standard lab-scale method as a reliable sludge dewatering index, able to reflect the efficiency of sludge dewatering.

1.9 Delineation

This study will only focus on waste activated sludge and polymer concentration. Only four MSWWTPs used in this study. The cost of the dewatering operation, the compression time of the bench press test, and gravity drainage tests using all four MSWWTPs and the two types of polymers. The Scientific Services Branch found at the City of Cape Town was used to obtain the parameters of the treated effluents. The researcher did not experimentally obtain these parameters.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The activated sludge process is used widely in wastewater treatment. However, it generates significant amounts of waste activated sludge (WAS) during primary, secondary, and tertiary treatment. The sources of solids in a treatment plant vary according to the type of plant and its method of operation (Metcalf & Eddy, 2003). For the treatment and disposal of the sludge produced at a wastewater treatment plant, it's crucial to know the characteristics of the sludge produced.

In this chapter, an explanation of the wastewater treatment process, mainly sludge and its' dewaterability, is provided. The wastewater treatment process consists of a preliminary step, followed by a primary, secondary, and then tertiary. The tertiary step discussed in this study is sludge dewatering by a belt filter press. The measures and assessment of the belt filter press will be in the form of lab-scale tests. These lab-scale tests involve gravity drainage as well as compression.

2.2 Origin of waste activated sludge (WAS)

At municipal wastewater treatment plants, raw municipal wastewater undergoes preliminary, primary, secondary, and tertiary treatment to yield treated effluent and a concentrated stream of solids in liquid, called sludge (National Research Council 1996, p. 45).

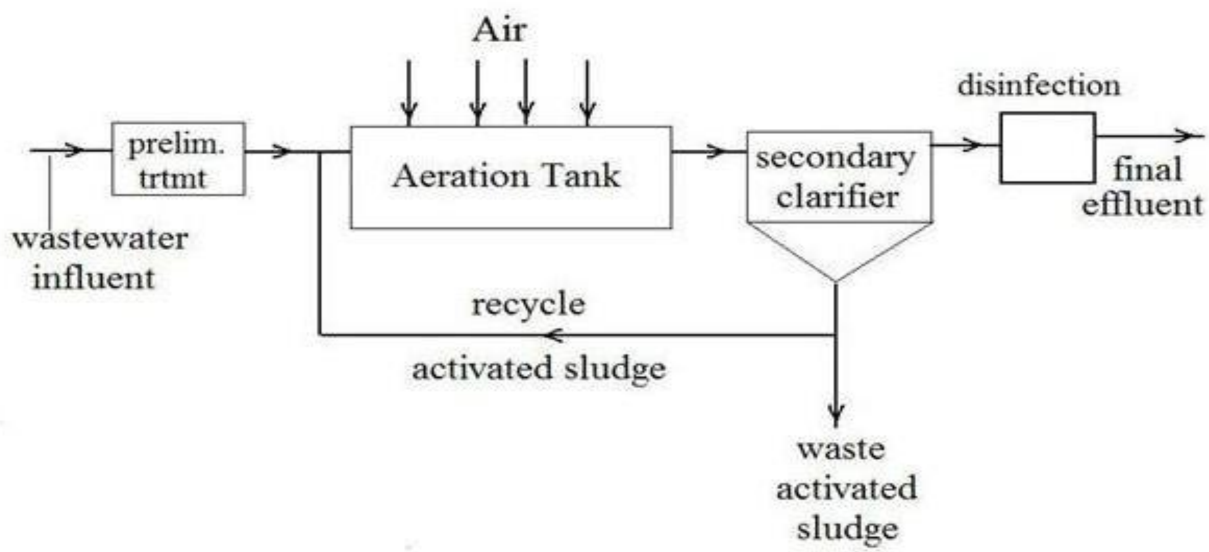


Figure 2.1: Municipal wastewater treatment process (Metcalf & Eddy, 1991)

The volume of wastewater sludge produced by wastewater treatment facilities is an uncertain quantity because it varies as a result of sludge treatment operation used, such as drying beds, digesters, belt filter presses, and centrifugation. Since the mass of dry solids during most treatment processes is essential to consider, the dry weight is a more useful basis for expressing the amount of sludge from municipal wastewater treatment. Typical primary and secondary wastewater treatment produces a total of about 0.94 kg of dry solids per 3.78 m^3 of the wastewater treated (Metcalf & Eddy, 1991).

2.3 Sludge composition

Biological waste activated sludge consists mainly of biological flocs that are formed by the growth of microorganisms and by adsorption of particles from the raw inlet flow. The flocs are microorganisms, single, fibers or microcolonies, organic fibers, inorganic particles (sand and salt), and extracellular polymeric substances (EPS)—a sketch of a typical sludge floc found in Figure 2.2.

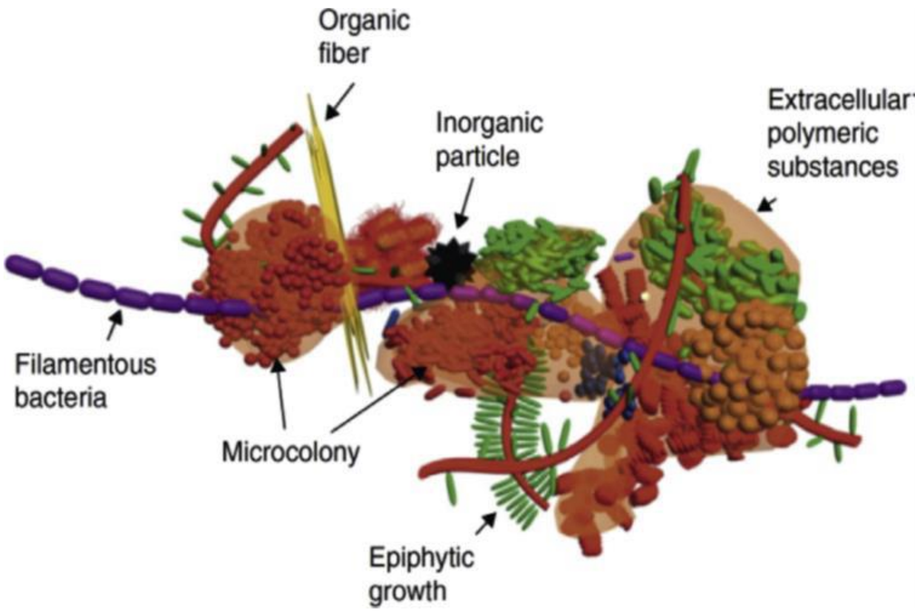


Figure 2.2: Sludge floc (Christensen et al., 2015)

The species composition of the activated sludge influences the floc properties to a certain extent, which in-tern affects the solid-liquid separation process. Some species form filaments, some strong microcolonies, and some weak flocs. They also produce different amounts and types of EPS with varying water-binding properties. The difference observed in the solid-liquid separation processes, such as belt filter presses, centrifugation, drying beds, etc., in different treatment plants is therefore caused by the difference in both microbial composition and water/floc chemistry (Christensen et al., 2015). Thus, several factors influence the dewaterability of sludge, such as physio-chemical properties of the feed, the biological treatment process, and the method used for sludge handling. On the other hand, the composition of the inlet raw flow entering the plant affects the properties of the sludge produced, especially the organic compounds, pH, and the ion composition. According to Christensen et al. (2015), floc and sludge properties have a significant impact on the specific filtrate flow rate. The best dewatering occurs when a sludge contains strong, compact flocs, low concentration of sludge cells, and dissolved EPS. This would result in the best settling in the clarifiers, the highest filterability, and the best effluent quality and lowers the number of chemicals required for conditioning of the sludge. High water hardness improves dewaterability due to the calcium ions improving floc strength, which also reduces the concentration of single-cell and EPS.

2.4 Moisture distribution in activated sludge

The liquid phase of sludge is divided into moisture or water types defined in terms of moisture to solids bond strength (Novak, 2006). The amount of moisture types influences the energy requirements for solid-liquid separation. Knowledge of the types of moisture found in sludge is vital to select the most cost-effective sludge volume reduction process. According to Novak (2006) and Mowla et al. (2013), proposed four kinds of moisture:

- Free water – water that is not associated with the solid particles, and is removable by gravity separation.
- Interstitial water – floc-entrapped moisture characterised by low binding energy and removable by the application of energy in the form of mechanical dewatering.
- Vicinal water – water held on to the surface of solid particles by adsorption and adhesion.
- The water of hydration – water absorbed by or strongly absorbed onto individual sludge particles, and removable by processes such as electro-osmotic dewatering and thermal drying

The water distribution in sludge is found in figure 2.3 below.

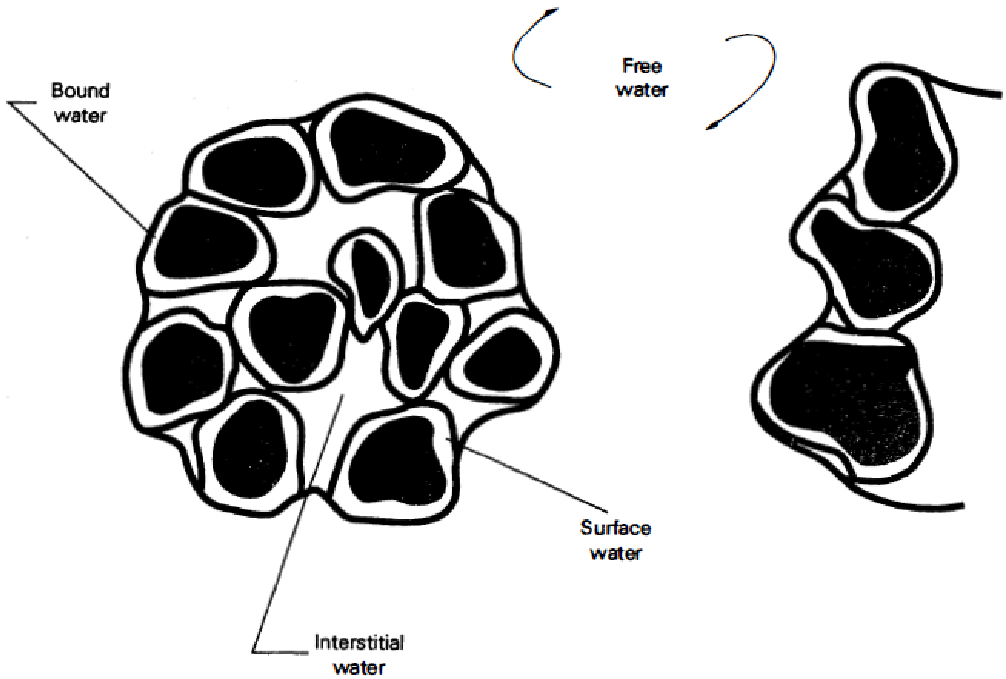


Figure 2.3: A conceptual visualisation of the moisture distribution in sludge (Tsang & Vesiland, 1990)

A useful approach to characterising the water associated with sludge is to measure the cake solids using standard techniques in a laboratory centrifuge or by pressing the sludge using a standard dewatering device such as a compression cell. Huang (1979) developed a more extensive relationship between the cake solids obtained by gravity settling and by mechanical dewatering utilising a series of laboratory devices. The results of his work can be seen in Figure 2.4.

The importance of his results is that each sludge contains a unique ability to retain water, and this influences the amount of water removed, regardless of the dewatering device.

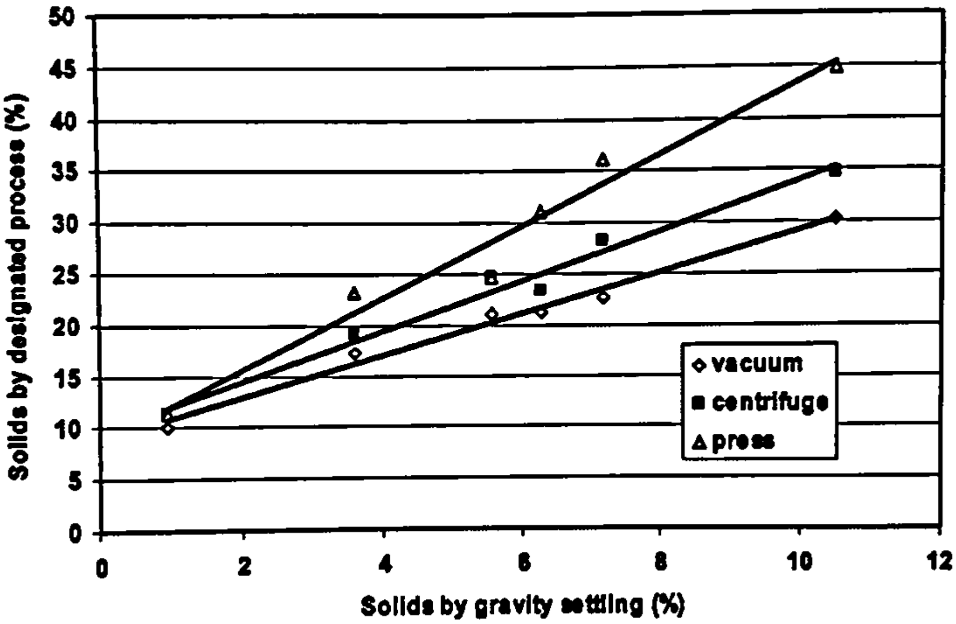


Figure 2.4: Comparison of cake solids by gravity thickening and selected dewatering processes (Huang, 1979)

2.5 Sludge characteristics

Wastewater sludge management operations require extensive sludge characterisation since wastewater sludges exhibit wide variations in their properties depending on the origin of the solids, the amount of aging that has taken place, and the type of processing to which they have been subjected (Metcalf & Eddy, 2003).

Sludge characteristics can be grouped into physical, chemical, and biological parameters. Physical parameters give general information on sludge processability and handleability. Chemical parameters are relevant to the presence of nutrients and toxic/dangerous compounds, so they become necessary in the case of utilisation in agriculture. Biological parameters give information on microbial activity and organic matter/pathogen presence. Table 2.1 below presents the physical, chemical, and biological parameters of wastewater sludge.

Table 2.1: Sludge characteristics parameters (Sanin et al., 2011)

Sludge characteristics	Parameters
Physical	Colour and odour Specific gravity Settle ability Drainability Floc/Particle size and shape Water distribution Filterability and Dewaterability Rheology Floc structure and porosity Floc density Thermal conductivity Fuel value or thermal content Compressibility Viscosity
Chemical	pH Alkalinity Solids concentration Surface charge and hydrophobicity Nutrients and fertiliser value Heavy metal and toxic organics Digestibility Fat content
Biological	Microbial community Surface polymers/Extracellular Polymeric Substances (EPS) Sludge stability

2.5.1 Parameters influencing sludge dewaterability

Various sludge parameters influence its performance during a dewatering operation. A few of these parameters selected for this study based on data available and the ability for them to be measured experimentally. The relative importance of these selective parameters and their impact on the bioflocculation of activated sludge is discussed in this section.

2.5.1.1 Concentration (g/l)

The solid concentration of the sludge will influence how flocculation will occur. The higher the concentration of the sludge, the harder it is to mix in a viscous solution of flocculant, the lower the consumption of flocculant. The flocculating ability is related to the sludges' specific resistance to filtration (SVI). Sludges with a high flocculating ability demonstrate high compressibility and settleable. The SVI parameter is discussed in more detail at a later stage of this literature study. The key factors influencing solid concentration in sludge are wastewater sources and sludge treatment processes. For example, industrial industry wastewater streams can significantly increase the sewage sludge quantity generated from a given amount of wastewater, which increases the number of solids found in sludge. Also, higher degrees of wastewater treatment generally increases sewage sludge volume (U. S. EPA, 1984).

2.5.1.2 Organic matter (%)

Sludge volatile solids (VS) are organic compounds that are reduced when heated to 550 ℃ under oxidising conditions. The VS content provides an estimate of the organic content of the material. The organic matter content is comparable to the Volatile Solids content (VS), the higher the VS, the more difficult the dewatering. The most unstable sewage sludge contains 75 to 85 % of VS on a dry weight basis. The dryness achieved will be low, the mechanical properties will be low, and the flocculant consumption will be high. When the VS of the sludge is high, it is recommended to add a thickening step in the process to achieve better dewatering.

2.5.1.3 The colloidal nature of the sludge

This characteristic has a significant effect on the dewatering performance. The higher the colloidal nature, the more difficult it is to dewater. Four factors will affect the colloidal nature of the sludge. The origin of the sludge, the freshness of the sludge will increase with its level of fermentation (septic sludge). The origin of the wastewater will increase the colloidal nature of the sludge. The sludge return, a poorly controlled returned activated sludge (RAS), will increase its colloidal nature (SNF Floerger n.d.).

Primary → Digested primary → Fresh mixed → Digested mixed → Biological

Low colloidal nature → **High colloidal nature**

2.5.1.4 Total Suspended solids

Turbidity in water is caused by suspended matter such as clay, silt, and organic matter, plankton, and other microscopic organisms that interfere with the passage of light through the water. Turbidity is closely related to total suspended solids (TSS), but also includes plankton and other organisms. The suspended or colloidal particles, commonly referred to as total suspended solids (TSS), are all the small suspended solids in water that will not settle out by gravity. Turbidity itself is not a significant health concern, but high turbidity can interfere with disinfection and provide a medium for microbial growth. It also is an indication of the presence of microbes (Nozaic & Freese, 2010).

Since turbidity and TSS are related, it can be said that a high TSS indicates high turbidity. High microbial growth will occur within a sludge with a high TSS. It could, therefore, be assumed that the freshness of the sludge would decrease, which would increase the sludges' colloidal nature, and consequently, the sludge will be difficult to dewater (Nozaic & Freese, 2010).

2.5.1.5 Volatile suspended solids

The volatile suspended solids (VS) is an important parameter to take into consideration when assessing sludge dewatering for a specific WAS. When it comes to mechanical dewatering, higher concentrations of solids in the feed sludge yields increased amounts of cake solids. It has also been shown that a longer retention time in the digestion process and, therefore, a lower VS percentage in the dewatered feed solids results in a greater dewatered cake solids concentration seen in Figure 2.5 (U. S. EPA, 1979).

Another parameter of concern would be the feed solids concentration of the WAS. Higher feed solids concentration generally results in drier dewatered cake concentration, as shown in Figure 2.6.

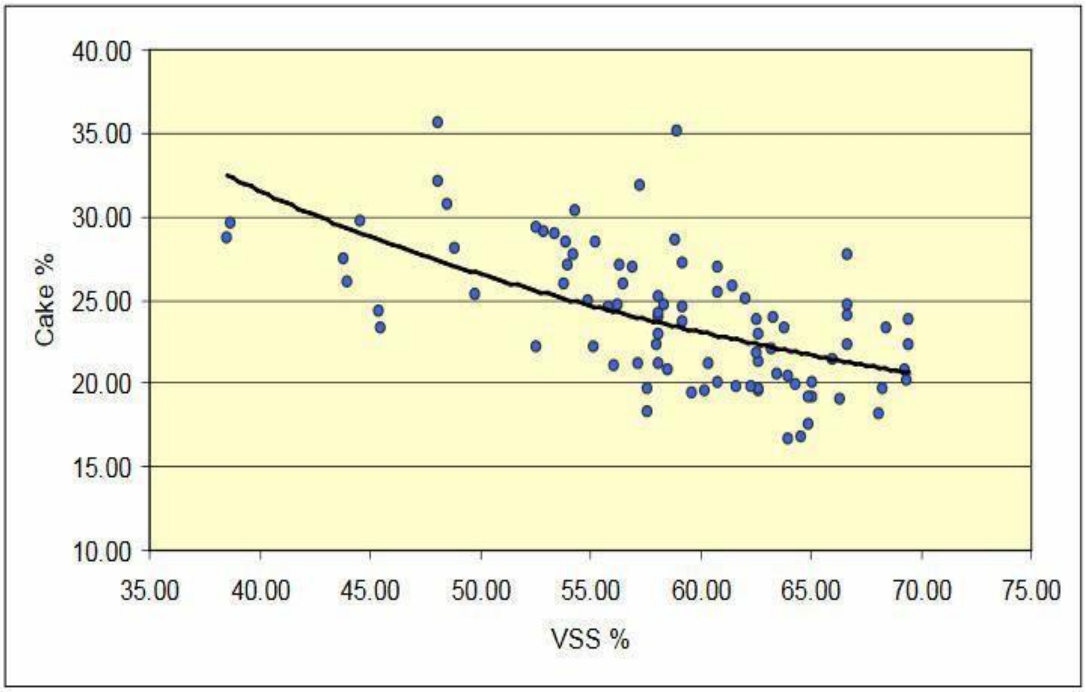


Figure 2.5: Relationship of Volatile Suspended Solids (VSS) to Cake % solids (U. S. EPA, 1974)

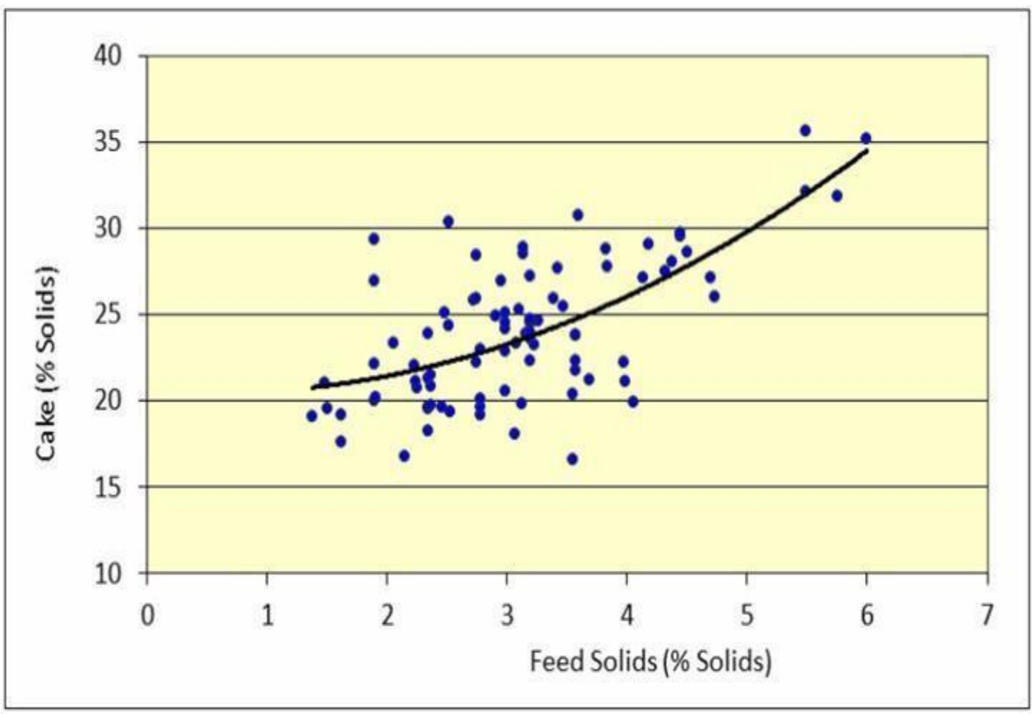


Figure 2.6: Relationship of Feed Solids (FS) to Cake % solids (U. S. EPA, 1974)

Oerke (2016) stated that "a pre-treatment process can increase the belt filter press dewatered cake solids concentration from aerobically and anaerobically digested bio-solids by 3 to 5 percent. It has been shown to significantly lower polymer consumption and results in an extremely clear filtrate". CH2M, a company that supplies dewatering equipment, utilised the technology in providing a bio-solids solution for a WWTP. A full-scale pilot test increased cake solids by 3 to 4 percent, reduced polymer uses by 30 to 40 percent, and increased the belt filter press throughput by 50 percent.

2.5.1.6 Sludge volume index (SVI)

According to (Raynaud *et al*.,2012), the SVI is calculated to describe how well the sludge from the aeration tank settles and compacts. An SVI of 80 mL/g or less usually indicates a sludge that is dense and has rapid settling characteristics. Most activated sludge plants seem to produce a clear, high-quality effluent with an SVI in the range of 100 to 200 mL/g. The sludge typically settles slower and traps more particulate matter as it forms a uniform blanket before settling. At this elevated SVI, the sludge settles very slowly and compacts poorly in the settle ability test. The mixed liquor suspended solids (MLSS) looks light and fluffy, not very dense. The SVI is calculated using equation 1.

$$\mathbf{SVI}\ \left(\frac{\mathbf{mL}}{\mathbf{g}}\right) = \frac{\mathbf{Settled\ Sludge\ Volume}\ (\frac{\mathbf{mL}}{\mathbf{L}})}{\mathbf{Mixed\ LIquor\ Suspended\ Solids}\ (\frac{\mathbf{g}}{\mathbf{L}})} \times \mathbf{1000} \quad \textbf{(1)}$$

2.6 Sludge treatment by means of thickening

The main objective of sludge treatment is simply the removal of water, stabilisation of the organic matter contained in sludge, destruction of pathogenic organisms, and disposal of the sludge in a safe and aesthetically acceptable manner (Sanin et al., 2011). The sludge treatment methods are thickening, stabilising, and finally dewatering the sludge.

The solids content of primary, activated, trickling-filter, or even mixed sludge varies considerably, depending on the characteristics of the sludge. Sludge thickening is a unit process used to increase the solids content of the sludge by removing a portion of the liquid fraction. By increasing the solids content, more economical treatment of the sludge can be affected. Sludge thickening processes include, but are not limited to, gravity thickeners, flotation thickeners, and belt filter press (U. S. EPA, 1982).

2.6.1 Gravity thickeners

Gravity thickening is most effective on primary sludge. Solids are withdrawn from primary treatment (and sometimes secondary treatment) and pumped to the thickener. The solids build up in the thickener forms a solids blanket on the bottom. The weight of the blanket compresses the solids on the bottom and "squeezes" the water out. By adjusting the blanket thickness, the percentage of solids in the underflow can be increased or decreased. The supernatant that rises to the surface is returned to the wastewater flow for treatment. Performance gravity thickeners (i.e., the solids concentration achieved) typically results in producing 8 to 10 % solids from primary underflow, 2 to 4 % solids from waste activated sludge, 7 to 9 % solids from trickling filter residuals, and 4 to 9 % from combined primary and secondary residuals (USEPA, 1982).

The performance of gravity thickening processes depends on various factors, including the type of sludge, condition of influent sludge, temperature, blanket depth, solids loading, and hydraulic loading. Figure 2.7 below represents the cross-sectional view of a gravity sludge thickener.

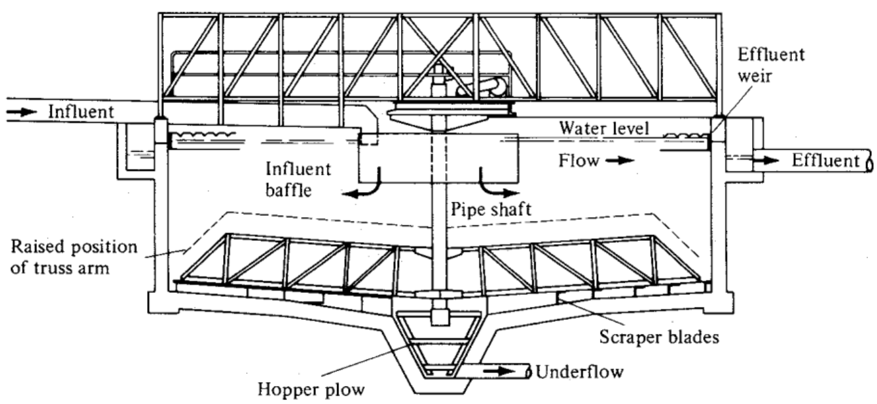


Figure 2.7: Cross-sectional view of a gravity sludge thickener (Wakeman, 2007)

2.6.2 Floatation thickening

Flotation thickening is used most efficiently for waste sludge from suspended growth biological treatment processes, such as the activated sludge process. In operation, recycled water from the floatation thickener is aerated under pressure. During this time, the water absorbs more air than it would under normal pressure. The recycled flow, together with chemical additives (if used), is mixed with the flow. When the mixture enters the flotation thickener, the excess air is released in the form of fine bubbles. These bubbles become attached to the solids and lift them towards the surface. The accumulation of solids on the surface is called the floating cake. As more solids are added to the bottom of the floating cake, a thicker floating cake is formed, and water drains from the upper levels of the cake. The solids are then moved up an inclined plane by a scraper and discharged. The supernatant leaves the tank below the surface of the float solids and is recycled or returned to the waste stream for treatment (U. S. EPA, 1982). Floatation thickener performance is typically 3 to 5 % solids for WAS with polymer addition and 2 to 4 % solids without polymer addiction. The most widely used flotation units are circular because they perform better in thickening applications. Indeed, due to the flotation unit design, the bubble bed covers the entire surface of the unit.

The performance of the dissolved air thickening process depends on various factors that include the bubble size, solids loading, sludge characteristics, chemical selection, and chemical dose. Figure 2.8 represents a schematic diagram of a dissolved air flotation system.

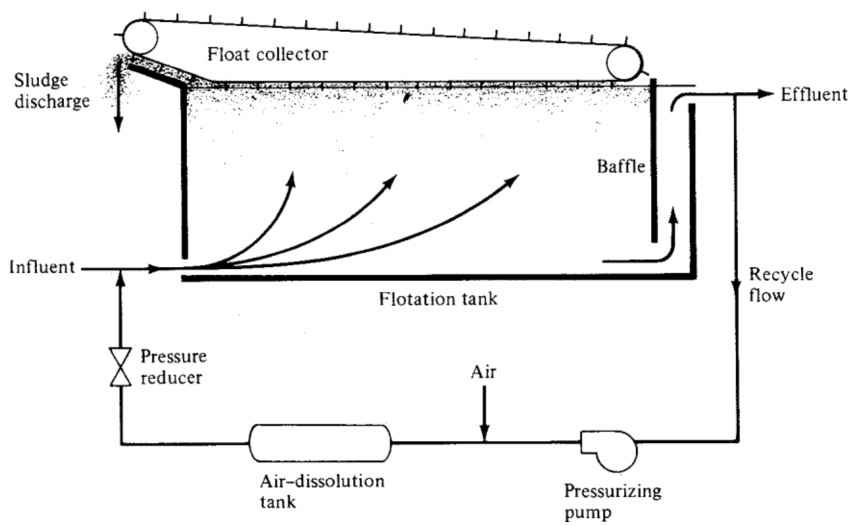


Figure 2.8: Schematic diagram of a dissolved air flotation system (Wakeman, 2007)

2.6.3 Belt filter press

Belt filter presses are one of the most common methods used for sludge dewatering to date. It is used to remove water from the waste activated sludge, which is generated during the wastewater treatment process, to produce a non-liquid material referred to as "cake." Dewatering serves the following purposes (U. S. EPA, 2000)

- It reduces the waste activated sludge volume generated, which intern reduces storage and transportation costs.
- Eliminates free liquids before landfill disposal.

- Reduces fuel requirements if the cake should be incinerated or dried.
- Produces a material which can be safe to use for composting when blended with a bulking agent.

2.6.3.1 Equipment description and operating principal

A belt filter dewaters by applying pressure to the biosolids to squeeze out the water. There are different types of belt filter press designs, but they all have the following characteristics (Wakeman, 2007):

- A flocculator, where the sludge is conditioned before entering the gravity drainage zone with a polymer that is used to aggregate the solids.
- Gravity drainage zone is where the initial dewatering takes place. The belt is supported horizontally without any pressure applied and allows the water to drain freely through the belt. Approximately one half of the water is removed in this zone.
- A progressive compression zone is where the sludge of the drainage zone is gradually compressed between two filter belts, the formation of the cake. Both compression and shearing take place in this zone.

The progressive pressurisation that takes place is up to 4 bars for low-pressure belt filters, up to 5 bars for medium-pressure belt filters, up to 7 bars for high-pressure belt filters, and a cake scraping zone. Once pressed, the cake is then scraped off from the surface of the two belts that separate at this point.

2.6.3.2 Main parameters influencing the belt press operation

The main performance parameters of a belt filter press are the hydraulic and solids loading rates, polymer dosage, solids recovery, cake dryness, wash-water consumption, and wastewater discharge. Hydraulic loading is expressed in cubic meters of sludge feed per meter per hour. Solids loading is described as the pounds of total dry solids feed per meter per hour (kilograms per meter per hour). The polymer dosage is calculated as kilograms per ton of total dry solids in the feed. Although the fraction of solids recovery is the number of dry solids in the cake divided by the dry solids in the feed sludge it is often calculated based on the suspended solids in the wastewater (filtrate plus wash water) represented in equation 2 below and figure 2.9 illustrates a schematic diagram of a belt filter press. (Olivier & Vaxelaire, 2005).

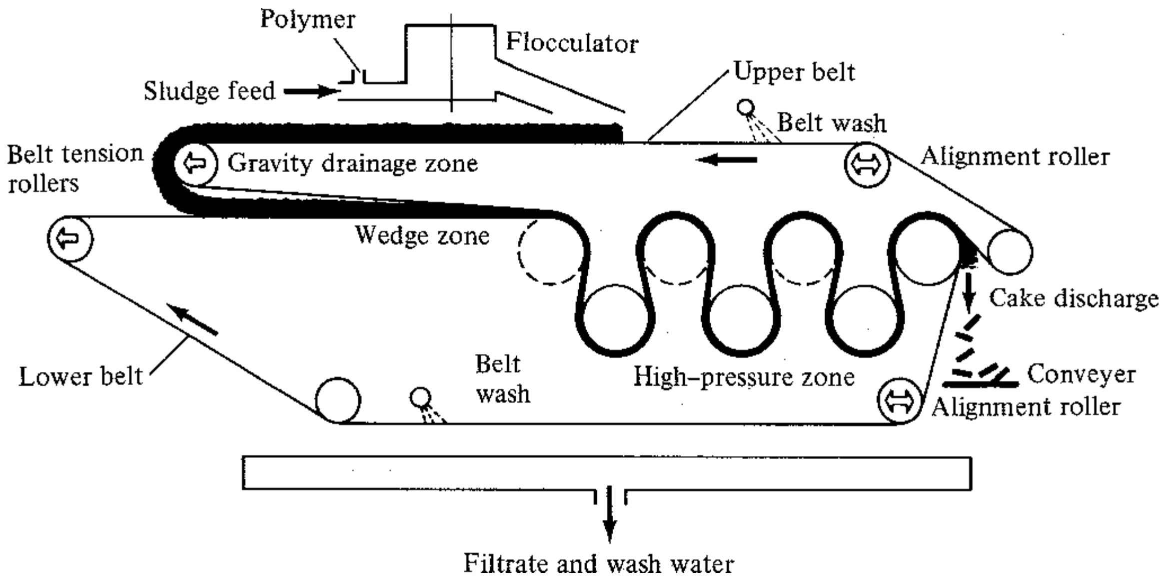


Figure 2.9: Schematic diagram of a Belt Filter Press (Wakeman, 2007)

$$\textbf{Solids Recovery}\ (\%) = \frac{\textbf{TS in feed sludge}\ (\frac{\textbf{mg}}{\textbf{L}})}{\textbf{SS in wastewater}\frac{\textbf{mg}}{\textbf{L}}} \quad \textbf{(2)}$$

Cake dryness is expressed as the percentage of dry solids by weight in the cake. For easy comparison with hydraulic sludge loading, wash water consumption, and wastewater discharge are usually expressed in cubic meter per hour per meter of belt width. A sample of the cake to the press, cake discharge, and filtrate should be taken at least once per shift and analysed for total solids (U. S. EPA, 2000) in Table 2.2 below, data used for a specific sludge generated within a municipal wastewater treatment is presented.

Table 2.2: Typical data for various types of sludge dewatered on belt filter presses (Wakeman, 2007).

Type of wastewater sludge	Total feed solids (%)	Polymer (g/kg)	Total cake solids (%)
Raw Primary	3 to 10	1 to 5	28 – 44
Raw WAS	0.5 to 4	1 to 10	20 – 35
Raw Primary + WAS	3 to 6	1 to 10	20 – 35
Anaerobically Digested Primary	3 to 10	1 to 5	25 – 36
Anaerobically Digested WAS	3 to 4	2 to 10	12 – 22
Anaerobically Digested Primary + WAS	3 to 9	2 to 8	18 – 44
Aerobically Digested Primary + WAS	1 to 3	2 to 8	12 – 20
Oxygen Activated WAS	1 to 3	4 to 10	15 – 23
Thermally conditioned Primary + WAS	4 to 8	0	25 – 50

2.6.3.3 Costs

The sludge handling section of Wastewater Treatment facilities is costly which can amount to approximately 50% of the plant's total operating cost (Boran *et al*., 2010). Therefore, it is crucial to optimise sludge management so that the cost of sludge processing is as low as possible. Capital cost for belt filter presses varies with the size of the equipment. It differs from six million dollars (0.5 m belt) approximate capacity of 200 dry kg/ hr. to ten million dollars with an approximate capacity of 700 dry kg/hr. These estimates are based on a feed material, which is 5% solids (Mowla *et al*.,2013).

2.6.3.4 Troubleshooting sludge dewatering operations

The quality of the sludge flocculation plays a major role in the results: sludge flow, filtrate quality, cake dryness. On belt filter presses, it is easy to check the quality of the flocculation in the drainage zone (SNF Floerger n.d.). The three main operating problems are inadequate drainage, sludge creep, and low cake dryness.

2.6.3.4.1 Inadequate Drainage

According to SNF Floerger n.d. when the drainage is insufficient, the following parameters must be checked. The mixing of sludge with the flocculant solutions must be optimal to obtain the best floc size. To achieve this, the following is necessary, a sufficient mixing intensity, the best injection point, and the sludge distribution on the belt.

Belt cleaning is another operating method to check. Thus, if the belts themselves are not perfectly clean, it's not possible to have good drainage since the pores are blocked. Therefore the following needs to be checked, the cleaning water flow may be too low, the cleaning water pressure may be too low and or the cleaning nozzles may be blocked. The belt pressure can also influence pore plugging. If the higher water pressure is used for belt cleaning, it may cause sludge to drain through the belt. If the flocculation quality is not optimal, drainage will be lower. The sludge and flocculant flow then need to be adjusted

2.6.3.4.2 Sludge creep

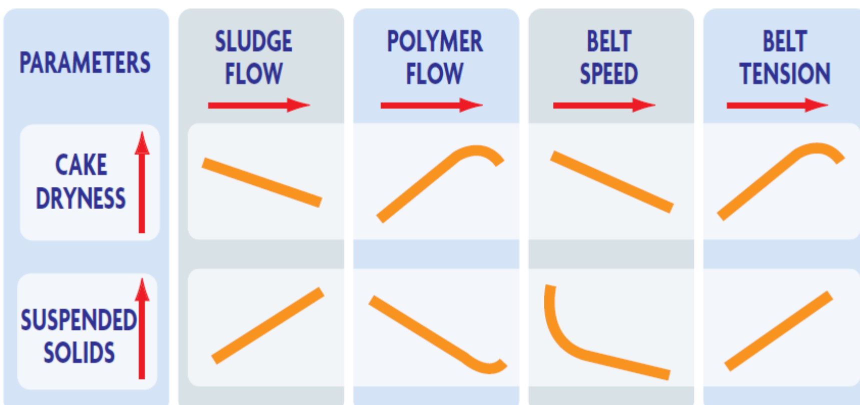
Sludge creep (squeeze out) frequently happens on biological sludge, which is difficult to dewater and sensitive to pressure. The three parameters that need to be modified to avoid sludge creep from occurring are as follows (SNF Floerger, n.d.), flocculation, drainage, and sludge feeding.

For flocculation, the optimal dosage is necessary for the best results. With gravity drainage, the faster the water is released, the dryer the sludge is when reaching the compression zone. Checking the initial drainage to obtain maximum water release and checking the cleaning of the belts is a proposed solution. When looking at the feed of the sludge entering the dewatering process, lowering the sludge flow, reducing the width of the drainage zone, and optimising the cake thickness are the parameters to check (SNF Floerger n.d.).

2.6.3.4.3 Low cake dryness

When modifying the belt filter press parameters, better dryness can be achieved, such as the mixing conditions, belt speed and tension, polymer selection, and cake thickness.

If mixing is not proper, cake dryness may be reduced. If the belt speed is high, the drainage time is short. By decreasing the belt speed, the drainage time is longer, and therefore the drainage is better. The belt pressure is an essential factor to get a good cake dryness. By increasing the belt pressure, better dewatering is obtained (Olivier & Vaxelaire, 2005). An accurate polymer selection will give the best results, such as changing the molecular weight, the structure of the polymer, and its dosage. The cake thickness should be adjusted, taking into account the intrinsic characteristics of the sludge.



Note:
shows an increase of the parameter and indicates the trend in dryness or in Suspended Solids. For example, when the sludge flow increases, the dryness decreases and the Suspended Solids in the filtrate increase .

Figure 2.10: Summary of the adjustable parameters (SNF Floerger, n.d.)

Figure 2.10 typically explains the trend the results of a belt press test could follow. According to these trends, the results obtained can be interpreted. For instance, for an increase in cake dryness, the sludge flow should be reduced, with an increase of polymer flow, a reduction in the belt speed with an increase in belt tension.

2.7 Sludge conditioning

To improve sludge dewaterability, proper sludge conditioning is a prerequisite. Conditioning is intended to alter sludge properties to achieve effective dewatering. This is usually attained in three different ways, as proposed by Rey & Varsanik (1986). By coagulation or flocculation of sludge solids particles to improve the settling ability of the sludge. Secondly, by reducing the sludge solid's compressibility to improve sludge cake filterability. Lastly, by the disintegration of sludge using techniques such as ozonation, enzyme treatment, or sonication for rupturing flocs or cells to release the trapped (bound) water molecules from extracellular polymeric substances (EPS). The known methods of conditioning can be categorised as physical or chemical methods.

2.7.1 Thermal pre-treatment

A well-known method for sludge conditioning is thermal pre-treatment. In this method, liquid sludge is heated in the temperature range of 60 – 180℃. Although the lipids and carbohydrates of sludge are easily degradable, the proteins are protected from enzymatic hydrolysis by the cell wall. Thermal pre-treatment in this stage can destroy the cell wall and release the proteins for biological degradation. In this process, the sludge gel network is broken, and the water affinity of the sludge solid is decreased. The degree of disintegration depends on the applied temperature and holding time. A temperature of 175 ℃ has been reported as the optimum for digested and undigested sludge with 10 – 30 minutes of holding time. The viscosity of heat-treated sludge decreases significantly, and this also improves the filterability of the treated sludge (Rey & Varsanik, 1986).

2.7.2 Biological or enzyme conditioning

Biological or enzyme pre-treatment of sludge can improve its dewaterability by weakening the gel structure of the flocs through the hydrolysis of EPS present in the sludge. Since enzymes are proteins and therefore considered environmentally friendly, this method can be very attractive, especially if it replaces acrylamide based synthetic polymer which is neurotoxic (Rey & Varsanik, 1986).

2.7.3 Chemical conditioning

The chemical conditioning step is carried out before the dewatering, and the purpose is to improve the efficiency of the dewatering procedure (Sanin et al., 2011). The aim of using conditioners is to break the gel-like layer. Furthermore, to increase the size of the particles would be to combine smaller particles into larger aggregates. The interaction within the sludge particles is typically negatively charged and repel each other rather than attract. Therefore, conditioning is used to neutralise the effects of this electrostatic repulsion so that the particles collide, which increases the size of the aggregate (Lee et al., 2005). Commercial synthetic polymers are generally defined as either non-ionic, cationic, or anionic. The type of ionogenic group on the polymer is instrumental in determining the effectiveness of a flocculant, which depends on its ability to attach to a particle. Adsorption may occur by electrostatic attraction, chemical bonding, hydrogen bonding, hydrophobic association, complex formation, or several other means (Linke & Brooth, 1968).

Proper conditioning of the sludge may be the most critical factor for optimum equipment performance. Sludge conditioning is a function of polymer dosage, dilution water, and mixing energy.

2.7.3.1 Physical forms of polymers and their application

Polymers are usually supplied in either dry, solution, water-in-oil emulsion, or gel form (Leopard & Freese, 2009).

Table 2.3: Physical forms of polymer and their application (Leopard & Freese, 2009).

Polymer physical form	Application
Solution polymers	2.7.1.1 Does not require a mixing tank 2.7.1.2 Typical forms are cationic homo and copolymers and low molecular weight hydrolysed poly (acrylamides) 2.7.1.3 Liquid polymers containing 10-50% active material are lower molecular weight products 2.7.1.4 Higher molecular weight polymers produce very viscous solutions and have less than 10% active material in solution 2.7.1.5 Cold temperature increase viscosity and may cause difficulty in handling
Dry polymers	2.7.1.6 Provides the most active material on an 'as product' basis 2.7.1.7 Finer the particles size, the greater the solubility, however, dusting increases 2.7.1.8 A holding day tank is often used 2.7.1.9 Feeding of the dry polymer too fast is the leading cause of fisheyes 2.7.1.10 High-speed mixing (>500rpm) or excessive mixing time (>1hr) are discouraged because a loss of polymer performance can occur. 2.7.1.11 High levels of dissolved solids and dissolved oxygen can reduce polymer effectiveness 2.7.1.12 After 24hrs, dilute polymer solutions in deionised water are much more effective than those prepared in hard water. 2.7.1.13 The viscosity of the polymer solution limits the maximum solution strength to 0.5% for anionic polymers and 1.0% for cationic and non-ionic

Emulsion polymers	2.7.1.14 Contains 25 to 60% active material, cationic polymers can range up to 60% 2.7.1.15 High molecular weight anionic and non-ionic polymers include 25 to 35 % active material 2.7.1.16 The polymer solution can be prepared in less than 30 mins 2.7.1.17 0.5 % active material will ensure complete inversion, the flocculant passes from the continuous oil phase to a continuous water phase. 2.7.1.18 Non-ionic emulsions invert more slowly than the higher charge polymers 2.7.1.19 Anionic and non-ionic emulsions have been successfully prepared as a 0.05% solution on an active material basis 2.7.1.20 Emulsions are more effective when prepared in potable water or soft water 2.7.1.21 Advantage of emulsions are higher percent active than liquid, and faster make down than the dry polymer 2.7.1.22 An automated bulk feed system can be installed to minimise operator supervision
Gel polymers	2.7.1.23 High molecular weight product 2.7.1.24 They have found application in areas where no electricity is available 2.7.1.25 The gel log can be placed in water and allowed to dissolve slowly

Table 2.4: Main parameters to consider for the water typically used for polymer makeup water quality (SNF Floerger, n.d.).

Parameters	Effects	Recommended values
Temperature	Fastest dissolution in warm water, but vapor can create problems (lumps). Hydrolysis of cationic products also increases	10 to 30°C
pH	High pH causes hydrolysis of cationic polymers. Low pH causes precipitation of anionic polymers	6 < pH < 8
Hardness	Hydrolysis of cationic polymers (high buffer effect on pH). Precipitation of anionic polymers (especially high charge)	< 300 mg/l $CaCO_3$
Conductivity	High conductivity decreases the dissolution speed and polymer solution viscosity	< 1000 µS/cm
Suspended solids	Suspended solids with be flocculated in the make down tank. This creates skin and blockage of pumps and lines	< 5 mg/l
Bivalent ions (Fe^{2+}, Cu^{2+},…)	They can initiate free radicals which will cleave polymer chains and decrease efficiency	< 1 mg/l
Residual oxidiser (eg., Chlorine)	Degradation of polymer chains	< 0.5 mg/l
H_2S	Creation of free radicals	0
Photo-oxidation	Free radicals degradation due to UV	Avoid exposure to light and UV
Bacteria (1000 CFU per 100 ml)	Bacterial growth, odor production and rapid degradation of polymers	0

2.8 Polymer Degradation

Polymer degradation can be separated into two mechanisms: hydrolysis and oxidation. Hydrolysis is derived from a combination of ancient Greek words hydro and lysis, hydro meaning water and lysis meaning to unbind. The definition of hydrolysis is therefore a chemical decomposition in which a compound is split into other compounds by reacting with water. Hydrolysis is the opposite of condensation, where condensation is the formation of water which is accompanied by the growth of polymer chains; in hydrolysis the reaction with a water molecule results in the breakage of polymer chains. Degradation is due to a change in the chemical and/or physical structure of the polymer chain, this leads to a decrease in the molecular weight of the polymer (J. Speight, 2011).

Hydrolysis is accelerated with the presence of small amounts of catalysts within water. These catalysts could be the presence of any ions within the water. The rate of hydrolysis doesn't only depend on the vulnerable chemical bonds within the polymer but also on the concentration of water inside the material. Hydrophilic polymers "water loving" are more vulnerable to hydrolysis and subsequent hydrolytic degradation as compared to hydrophobic polymers "resistant to water". There are several factors that affect the hydrolytic stability of polymers. The most important are pH, temperature, hydrophobicity, morphology, degree of crystallinity and porosity (J. Speight, 2011).

2.9 Sludge dewatering index

Dewatering processes in everyday use, such as pressure filters, vacuum filters, and centrifuges, require for their design some measure of the sludge dewatering characteristics. Two alternative methods are used to measure the ease of dewatering, specific resistance to filter (SRF), and capillary suction time (CST). Particularly specific resistance to filtration, r, is the most commonly used measure of sludge dewatering characteristics. It is determined using a laboratory apparatus by filtering a sample of sludge under an applied vacuum. During the test, the volume, V, of filtrate is noted at regular time intervals. The slope of the straight line of best fit to the data is then used to calculate the value of specific resistance to filtration (Sanin *et al*., 2011).

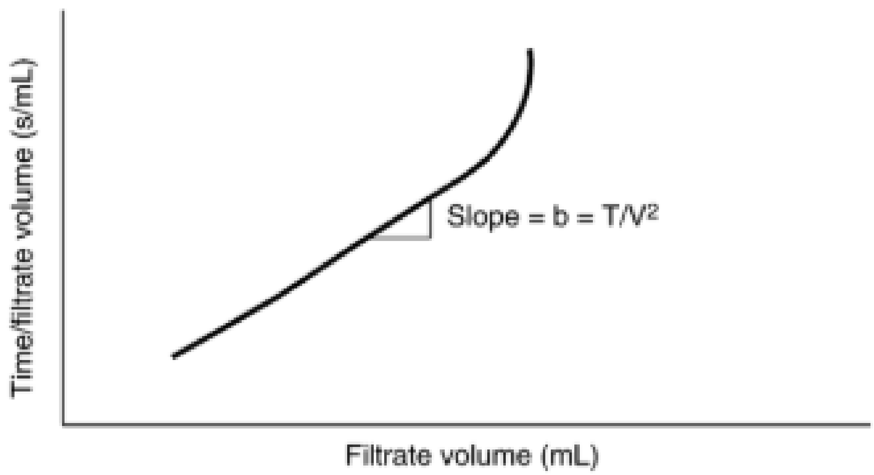


Figure 2.11: Time/filtrate volume vs. filtrate volume plot (U. S. EPA, 1982)

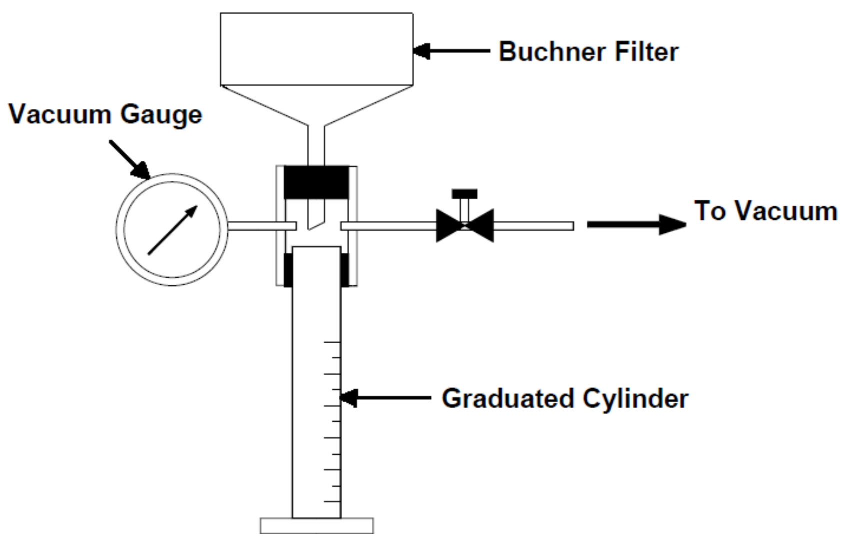


Figure 2.12: Apparatus for the determination of specific resistance to filtration (Sanin et al., 2011).

The higher the specific resistance, the more difficult it is to dewater sludge and vice versa. Specific resistance varies with applied pressure, filter area, pore size, and liquid viscosity, making it more complicated to measure and compare (Sanin *et al*., 2011). In Figure 2.13 below, as the graph dips and then starts increasing, at the turning point shown, optimum conditioning of the flocculant used would be achieved.

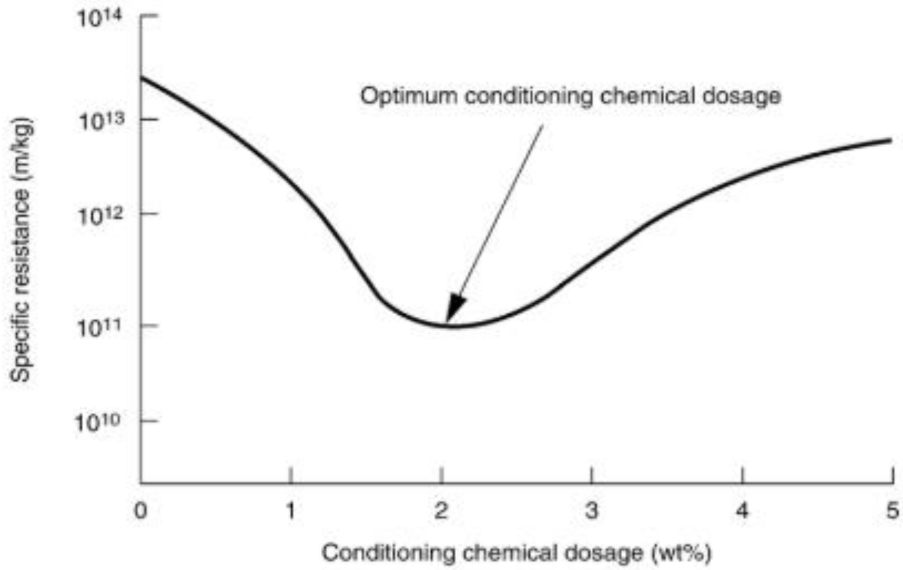


Figure 2.13: Effect of polymer dose on specific resistance to filtration (Sanin et al.2011)

The specific resistance to filter (SRF) equation is derived from the filtration theory which has been developed over the years based on the pioneering work by Ruth (1946), Carman (1938), Coackley & Jones (1956) from the one-dimensional Darcian flow, no mass transfer between liquids and solids, insignificant gravitational forces and a negligible solid velocity compared to the liquid viscosity (Soerensen & Soerensen, 1997).

$$\mathbf{q} = \frac{\mathbf{1}}{\boldsymbol{\alpha\mu}}\frac{\mathbf{dp_1}}{\mathbf{d\omega}} \quad \textbf{(3)}$$

Where: q is the liquid flux relative to the solids (m/s);

μ is the liquid viscosity (Pa.s);

α is the local specific resistance (m/kg);

ω is the position in the cake in the form of amount of solids deposited per unit cross-section area (kg/m^2).

The dewatering of a suspension in a filtration experiment working under constant pressure is well described by the t/V versus V plot. The linear part represents the filtration phase. It corresponds to the formation of the cake due to the accumulation of the solid particles on the surface of the filter cloth. The ability of the forming cake to allow water to pass through is commonly represented, during the filtration phase, by the SRF. This parameter is classically calculated by the slope of the linear part according to the following equation (Qi et al., 2011 & Carmen, 1938):

$$\frac{t}{V} = \frac{\mu SRF\omega}{2PA^2}V + \frac{\mu R_m}{PA} \quad (4)$$

Where: V is the volume of filtrate (m^3);

t is the time (s);

P is the vacuum (Pa);

A is the filtration area (m^2);

μ is the filtrate viscosity (Pa.s);

r is the specific resistance to filtration (m/kg);

C/ω is the suspended solids concentration (kg/m^3), and

R_M is the initial resistance of filter medium.

The use of this relationship implicitly supposes a constant porosity through the cake thickness. This is not true in activated sludge cakes, which are highly compressible (Sorensen & Hansen, 1993). Most investigators determine SRF using the following equation (Christensen & Dick, 1985)

$$SRF = \frac{2\Delta PA^2 b}{\mu\omega} \quad (5)$$

Where: ΔP is pressure difference (for filtration process, pressure difference refers to liquid pressure) (Pa);

A is filtration area (m^2);

b is the line ‘s slope;

μ is viscosity (Pa. s);

ω is weight of dry cake solids per unit volume of filtrate (kg/m^2).

For this study, the pressure would refer to the pressure caused by the liquid calculated using equation 6:

$$P = h\rho g \quad (6)$$

Where: P is liquid pressure (Pa);

h is height of the sludge volume (cm);

g is gravitational constant (m/s^2)

The weight of dry cake solids per unit volume of the filtrate was calculated using equation 7:

$$\boldsymbol{\omega} = \mathbf{C} = \frac{\mathbf{1}}{\frac{\mathbf{C_1}}{\mathbf{100-C_1}} \times \frac{\mathbf{C_f}}{\mathbf{100-C_f}}} \qquad \textbf{(7)}$$

Where: C is the solids deposited per unit volume of filtrate (g/ml);

C_1 is the moisture content of the feed (mg/l);

C_f is the moisture content of the cake (mg/l).

The specific resistance to filter (SRF) was calculated and obtained by equation 4. The ability of the forming cake to let the water go through is commonly characterised, during the filtration phase, by the SRF, which is also considered a dewatering index rather than a designing parameter (Vaxelaire & Olivier, 2007). A sludge of high specific resistance is more difficult to dewater than one of low specific resistance. Sludge's with an SRF of $> 10^{14}$ m/kg are challenging to dewater. Conventional dewatering by methods such as filter pressing is feasible for r ~ 2 x 10^{12} m/kg. It should be noted, however, that the value of SRF depends closely on the nature of the sludge solids and the mechanism by which water is retained within the solid's matrix that, for designing dewatering facilities, it is necessary to determine the value of r for the particular sludge concerned.

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the details of the apparatus, experimental procedures, and materials used to gather the necessary data to evaluate the sludge dewatering belt press. The sludge dewatering belt press consists of gravity drainage (linear screen) and compression (belt press) sections. Two independent experimental tests were conducted: the drainage control test, which simulated the linear screen, and the bench press, which simulated the belt press. Descriptions of the operating procedures will be presented, and the sludge characteristics will be assessed.

3.2 Research Design

The research design techniques used for this study consisted of both quantitative and qualitative experimental research. The four sections were as follows: sludge characterisation to determine optimum polymer demand (OPD), utilising four treated effluent types to see the effect they have on change in flocculant and flocculant concentration, gravity drainage, and compression. Statistical analysis was conducted to validate the data collected during the experimental runs.

3.3 Experimental details

There are many variables associated with assessing the dewaterability of municipal sludge that previous researchers have identified. For this study, four MSWWTPs within the CoCT (Plants A, B, C, D) were chosen. These MSWWTPs were selected based on their continuous operability and reliability when needing to collect sludge samples. Two polymers were used, FLOPAM 4650 and FLOPAM 4800. FLOPAM 4650 has a medium cationicity of 55% and FLOPAM 4800, a high cationicity of 80%. These two were selected based on availability. All the MSWWTPs within the CoCT are using one of these polymers at their dewatering facilities.

Various treated effluent types for flocculant dissolution were used, namely, treated effluent before filtration, treated effluent after filtration, MBR permeate, and potable water. Treated effluent before filtration is found after chlorination has taken place, this can be seen in Figure C.1 found in Appendix C. It's obtained via a filtration plant. This filtration plant uses sieves to remove solid particles that were unable to settle within the maturation ponds. The effluent flows through this plant before being discharged to the end-users. Treated effluent after filtration is the treated effluent provided to the end-users. The MBR permeate is the effluent produced via the MBR plant.

These 'water types' are currently being utilised at the MSWWTPs for flocculant dissolution and 'service water.' To obtain representative results of the full-scale dewatering operations, all four water types were investigated using the lab-scale sludge dewatering unit.

MSWWTPs sludge collection was only waste activated sludge (WAS). The experimental tests ran for seven months between March 2018 and December 2018. Each month a sample was collected in a sequence of Plant A, B, C, D. These MSWWTPs were far from each other, and it was not practical to collect the samples all at once. The sampling took place as follows:

Table 3.1: Sampling dates for each WWTP

Sample dates 2018														
WWTP	March		April		May		June		July		August		September	
	7	14	10	24	2	16	12	26	9	24	14	28	11	25
A	×				×				×					
B		×				×				×			×	
C			×				×				×			
D				×				×				×		×

Plant D was the furthest and had the highest feed solids concentration due to a thickening step before the sludge dewatering facility. At Plant D, the poly - flocculant used was FLOPAM 4800, while the other three MSWWTPs are using FLOPAM 4650.

3.4 Sampling methods

The waste activated sludge (WAS) was collected from the four MSWWTPs in 20-liter drums. In Table 3.2 the general information for the four WWTPs used for this research is presented.

Table 3.2: General information on four WWTPs for this study

WWTP	Polymer used	Polymer concentration (%)	Poly consumption Kg/DTS	Dilution water used
A	Flopam 4650	0.25	1.5	Treated effluent before filtration
B	Flopam 4650	0.25	4.1	MBR Permeate
C	Flopam 4650	0.25	4.5	MBR Permeate
D	Flopam 4800	0.30	5.6	Treated effluent before filtration

3.4.1 Sludge Collection and Characterisation

For MSWWTP A and C, the collection point of the WAS was at the dewatering facility at the sludge inlet valve coming from the wasting line. For MSWWTP B, the WAS were collected at the buffer tank, a holding tank that each reactor wasted to before wasting to the dewatering plant. At MSWWTP D, a thickening step before the dewatering plant occurred. This created the sludge sample to produce a high feed solids concentration, and this was due to sludge settling, which made a thicker sludge.

The following steps took place when sludge was collected at each WWTP:

1 The sludge sample was collected from the wasting line situated before the dewatering plant.

2 Samples were collected from the sampling points mentioned previously and then were immediately transferred to the laboratory for characterising their physical and chemical parameters (dry solids (DS) content, volatile solid (VS) content, total suspended solids (TSS) content and sludge volume index (SVI)) on the same day.

3 Samples used for conditioning tests were stored in the laboratory's fridge at 5°C and warmed up when needed, within four days after collection, to room temperature.

4 This was done to limit the biological activity and enable the acceptable reliability of the experiments.

5 All experiments were conducted in duplication.

6 A 500 ml mixed liquor (ML) sample for each MSWWTP was also collected. This was used to determine the sludge's sludge volume index (SVI).

3.4.2 Sludge parameters obtained

The following sludge characteristics were obtained before the lab-scale tests were conducted. This was needed at the beginning of the test work to get an understanding of the category the sludge fits into, and the steps are as follows:

1 The dry solids content of the WAS was determined by drying at 105°C using a moisture analyser ASTM Standard Test Method, on arrival to the laboratory.

2 The volatile suspended solids and total suspended solids where determined soon after the dry solid content of the sludge using method 1684 (EPA-821-R-01-015).

3 The sludge volume index (SVI) was calculated after the sludge sample had settled in a granular cylinder for 30 mins. The volume of the settled sludge was recorded in ml/l.

4 A mixed liquor sample was also collected because it's needed to calculate the SVI.

5 A settle ability test was also conducted on the mixed liquor sample in a 1000 ml granular cylinder; the unit for this test run is mg/l.

6 The SVI is the result of a mathematical equation calculated using Equation 2 in Chapter 2.

3.4.2 Treated Effluent

The 'water types' used for flocculant dissolution/conditioning were collected within the WWTPs used for this study before experimental tests were conducted and are presented in Table 5. Currently, the treated effluent after filtration is not being utilised for the dewatering facility

Table 3.3: Treated Effluent sample collection

Treated Effluent	Collection Point	WWTP using Effluent for Polymer make-up
Treated Effluent Before Filtration	Plant A	Plant A and Plant C
Treated Effluent After Filtration	Plant A	NONE
Membrane Bioreactor Permeate (MBR)	Plant B	Plant B
Potable water	Plant A	Plant D

It was needed to observe the difference, if any occurs, in sludge dewatering using both treated effluent types. Table 3.3 presents the parameters that need to be considered when selecting a 'water type' for polymer dissolution.

3.4.3 Conditioning

Two cationic polyelectrolytes (SNF Floerger, Andrezieux, France) one with medium charge density, FLOPAM 4650 (55%), and the other high charge density, FLOPAM 4800 (80%), were used to condition the sludge, which can be seen in Figure 3.1, a graph of polymer cationicity provided from the supplier SNF Floerger.

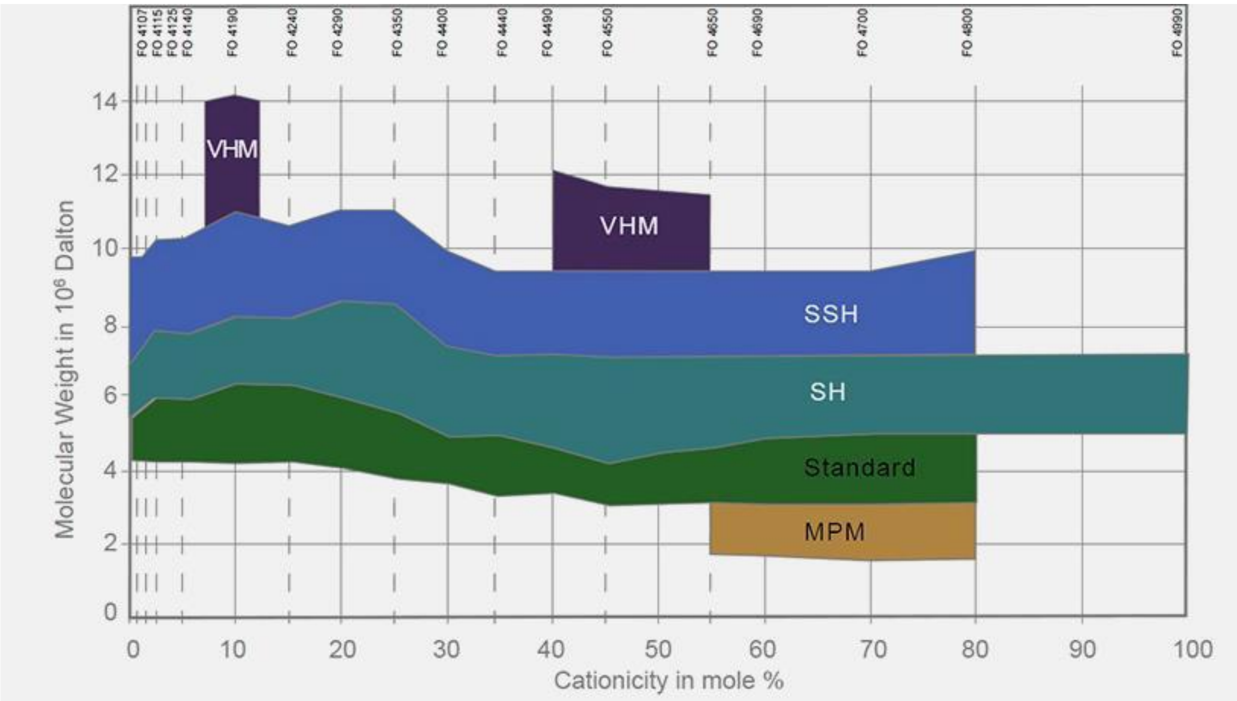


Figure 3.1: Cationicity vs. Molecular weight of cationic polymers (SNF Floerger n.d.)

The polymer-flocculant was prepared using the following steps:

1 The polymer solutions (2 g/l and 3 g/l) were prepared the day before its use.

2 A magnetic stirrer was used to mix the polymer with the water.

3 The polymer was measured using a TANITA mass balance, which is used specifically for small increments measurements since the measurement for the polymer was 0.5 g to make up the 2g/l concentration.

4 The 0.5 g was then slowly added to 250 ml water that was already mixing on the magnetic stirrer.

5 The solution (water and polymer) were mixed for 1 hour and allowed to age for 30 mins before use. The same procedure was applied to the 3 g/l concentration polymer solution, with 0.75 g mixed into 250 ml of water.

6 In Photograph 3.1, the Tanita mass balance used to measure small increments of polymer is presented.

Photograph 3.1: Mass balance

Photograph 3.2: Polymer addition

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3.5 Experimental set-up and procedures

3.5.1 Gravity drainage test

For this experimental test, a gravity drainage test was set-up via a computer program called the drainage control test. This experiment aimed to detect when overdosing of the polymer has taken place. This will be observed on the program via a graph of volume vs. time and will occur as soon as the chart starts overlapping the previous figure that was formed. The drainage control test program is a software installed on a laptop, which uses a Mettler balance to measure the volume of filtrate captured over time. The data can be imported to excel onto the connected laptop or used as-is. As soon as overlapping occurs, overdosing has taken place, which shows that the steady-state of the experiment has been attained. This experiment also showed one how different water types perform w.r.t gravity drainage, as well as how various sludges performed depending on their feed solids concentration. It also showed the different impact concentrations of the polymer have on gravity drainage (SNF Floerger, 2016).

The following steps were taken to achieve the outcome of this experiment:

1 Each test was conducted using 200ml of sludge.

2 Before the dosage of the polymer was selected, a simple calculation was conducted in excel to obtain the polymer consumption. The figure presented in Appendix A Figure A.3.1.

3 The polymer dosage added to the sludge will be decided depending on the polymer consumption obtained.

4 In Figures 3.2 and 3.3, a simple method is presented to select the polymer solution (ml) based on the sludge's dry solids content.

5 In Figure 3.2, the polymer dosage is selected at a specific sludge feed solids concentration to obtain the polymer volume required.

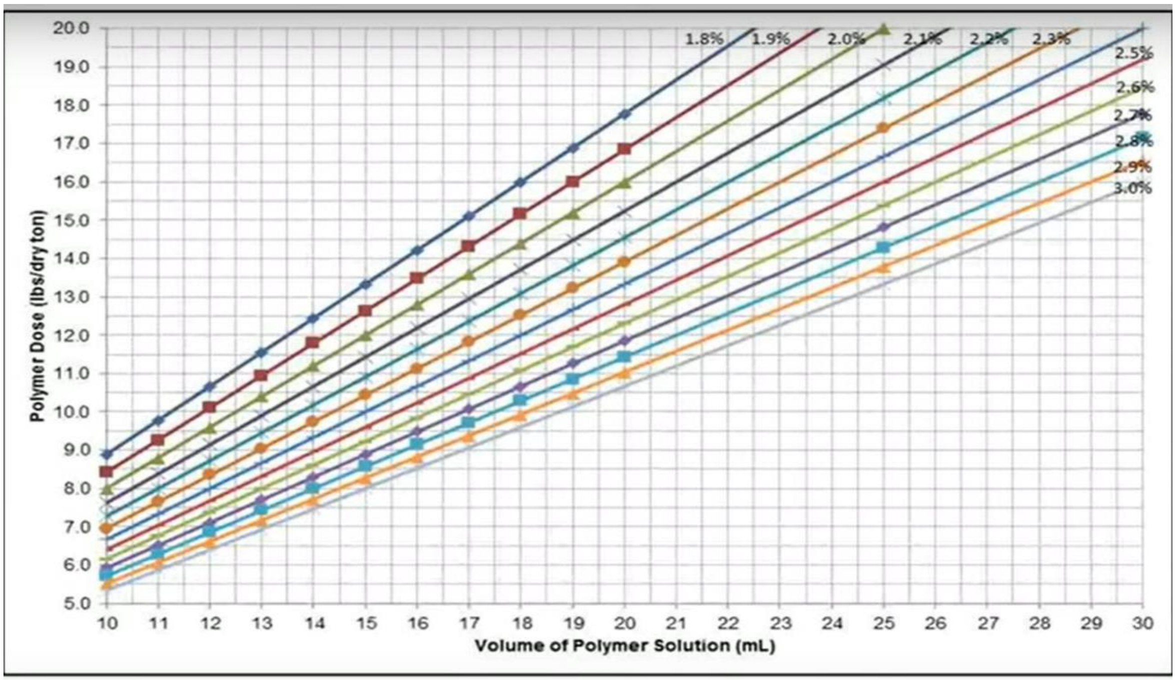


Figure 3.2: Conversion graph to select the volume of polymer

Either figure 3.2 or 3.3 can be used to select the volume of polymer based on the dose and sludge concentration.

	Sludge Total Solids Concentrations (% Solids)												
Volume (mL)	1.80%	1.90%	2.00%	2.10%	2.20%	2.30%	2.40%	2.50%	2.60%	2.70%	2.80%	2.90%	3.00%
10	8.9	8.4	8.0	7.6	7.3	7.0	6.7	6.4	6.2	5.9	5.7	5.5	5.3
11	9.8	9.3	8.8	8.4	8.0	7.7	7.3	7.0	6.8	6.5	6.3	6.1	5.9
12	10.7	10.1	9.6	9.1	8.7	8.3	8.0	7.7	7.4	7.1	6.9	6.6	6.4
13	11.6	10.9	10.4	9.9	9.5	9.0	8.7	8.3	8.0	7.7	7.4	7.2	6.9
14	12.4	11.8	11.2	10.7	10.2	9.7	9.3	9.0	8.6	8.3	8.0	7.7	7.5
15	13.3	12.6	12.0	11.4	10.9	10.4	10.0	9.6	9.2	8.9	8.6	8.3	8.0
16	14.2	13.5	12.8	12.2	11.6	11.1	10.7	10.2	9.8	9.5	9.1	8.8	8.5
17	15.1	14.3	13.6	13.0	12.4	11.8	11.3	10.9	10.5	10.1	9.7	9.4	9.1
18	16.0	15.2	14.4	13.7	13.1	12.5	12.0	11.5	11.1	10.7	10.3	9.9	9.6
19	16.9	16.0	15.2	14.5	13.8	13.2	12.7	12.2	11.7	11.3	10.9	10.5	10.1
20	17.8	16.8	16.0	15.2	14.5	13.9	13.3	12.8	12.3	11.9	11.4	11.0	10.7
25	22.2	21.1	20.0	19.0	18.2	17.4	16.7	16.0	15.4	14.8	14.3	13.8	13.3
30	26.7	25.3	24.0	22.9	21.8	20.9	20.0	19.2	18.5	17.8	17.1	16.6	16.0

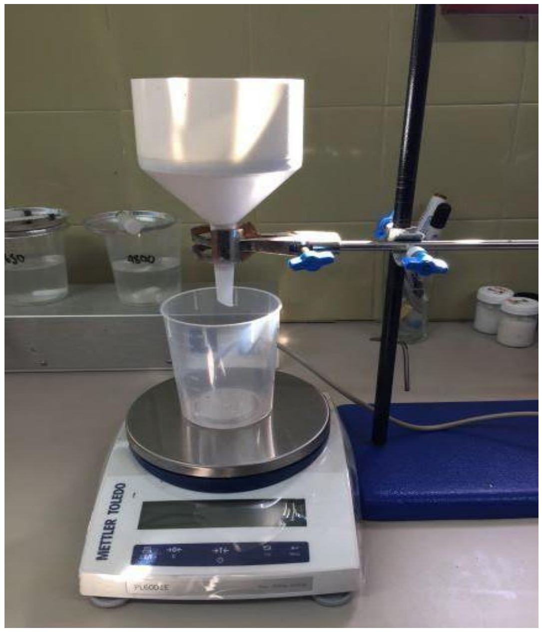
$$Polymer\ Dosage_{\left(\frac{lbs}{dt}\right)} = \frac{Volume_{poly}}{\%\ Total\ Solids} * \frac{4}{250} \qquad Volume_{polymer} = Polymer\ Dosage_{\left(\frac{lbs}{dt}\right)} * \%\ Total\ Solids * \frac{250}{4}$$

Figure 3.3: Conversion table to select the volume of polymer

For the conversion table Figure 3.3, the volume of polymer is the polymer dosage multiplied by the sludge feed solids. This variation in the polymer make-up will be used to obtain the underdose, optimum dose, and overdose for the polymer in ml.

3.5.1.1 Drainage control test

A drainage test will also be conducted using the Mettler Balance presented in Photograph 3.4.



Photograph 3.3: Filtrate Mass Balance

This test would provide (via a computer-linked scale), the weight of the drained filtrate. The computer recording of the drainage test is recommended since the first 10 seconds of the drainage are the most crucial (SNF Floerger n.d.).

1. In the drainage control test, the sludge mixed with the flocculant is induced at a given volume through a porous medium.
2. The solids present in the sludge mixture would be stained out of solution and deposited as a cake on the porous medium.
3. The drained water will be measured in the beaker, which measures it via the computer program that it's attached to. This drained water is referred to as the filtrate and will be measured and plotted on a graph against time, refer to Figure 3.4 below (SNF Floerger n.d.).

The parameters that were monitored are as follows:

- The drainage speed during the first 10 seconds
- The filtrate quality by visual inspection
- The efficiency of the polymer at low, optimum and high dosage
- The mixing ability of the polymer in the sludge

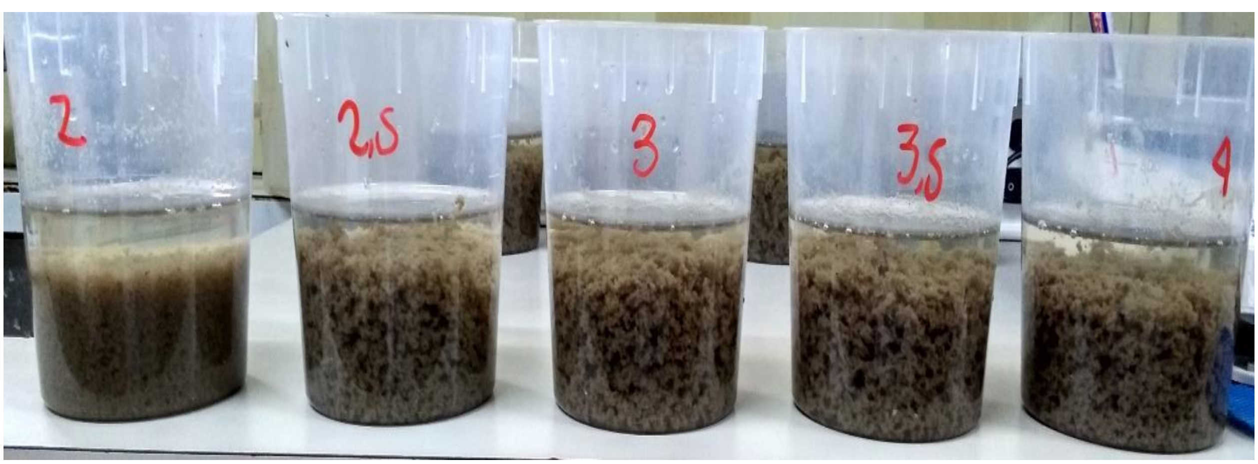
3.5.1.2 Jar test

Jar tests were used to determine the performance of sludge conditioning at the WWTP. Four main factors can influence the performance, water quality, mixing conditions, coagulant chemistry, and dosage rate. The figure below represents samples of before and after polymer dosing (SNF Floerger n.d.).

3.5.1.3 Pre-selection of flocculant dosage

The pre-selection of the polymer dosage took place before the experimental tests were done. This method was used to obtain the minimum, optimum, and overdosing polymer dosage. This was necessary to determine the polymer consumption (kg/DTS) required for each WWTPs WAS.

1. A screening test was conducted using the Jar test described in Chapter 3, and from this test, the polymer dosages were selected.
2. Minimum flocculation occurred when flocs just about start to form.
3. From this point, 1 ml was added to the next screening test, up until five polymer dosages were selected (SNF Floerger, n.d.) presented in Photograph 3.4, i.e., if 1ml was found to be the minimum dosage for flocculation to just about the start, this amount was used as the minimum. After that, 2 ml of flocculant was added to the next beaker of sludge, 3 ml to the next up until 5 ml of flocculant, which was added to the last beaker.
4. This procedure was applied to both polymers (FLOPAM 4650 and FLOPAM 4800) at different concentrations (2 g/l and 3 g/l)
5. All four' water types' and WAS's were tested using the above polymer concentrations.
6. The drainage curves were conducted for all the conditions, data presented APPENDIX A.



Photograph 3.4: Selection of polymer dosages

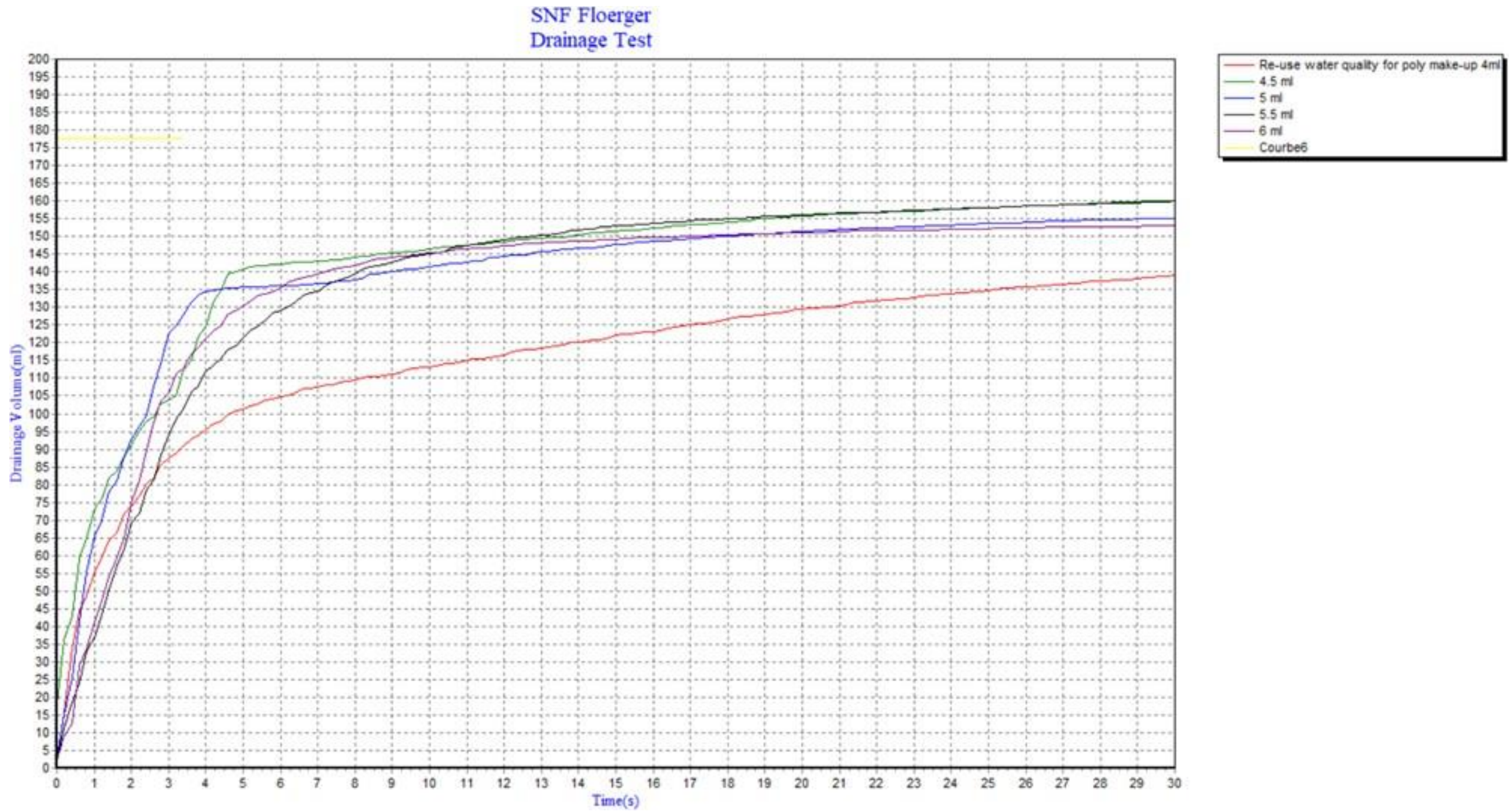


Figure 3.4: Drainage curve via the drainage control program (Mettler Toledo)

3.5.2 Bench press

The bench-scale dewatering tests, which consisted of the use of the bench press simulated the compression stage of the belt press.

Photograph 3.5: Bench press unit

1. The solids technology bench press rig was used to apply pressure to a sample of flocculated sludge, which was trapped between two circular filter discs.
2. These discs are made from the same fabric as the filter belts. The arrangement of the rig is shown in Photograph 3.5 and Figure 3.5.
3. A disc of filter belt material 75mm in diameter was placed on a perforated metal disc and seated in a plastic holder.
4. A sample of flocculated sludge was poured onto the filter belt, and free water drained through it the same way the gravity stage of a belt press operates.
5. After gravity drainage was completed, a second filter belt disc was placed on top of the sludge and a second perforated metal disc placed on top of it.
6. This effectively sealed the flocculated sludge between two filter discs in a similar manner to how sludge is trapped between two filter belts on a full-scale belt press.
7. After applying pressure to the upper, perforated disc pressure was applied to the sludge

sandwich, which forced out water that passed through the filter belts and the perforated plates (Solids Technology International Limited, 2001).

The figure below is the schematic diagram of the bench press apparatus

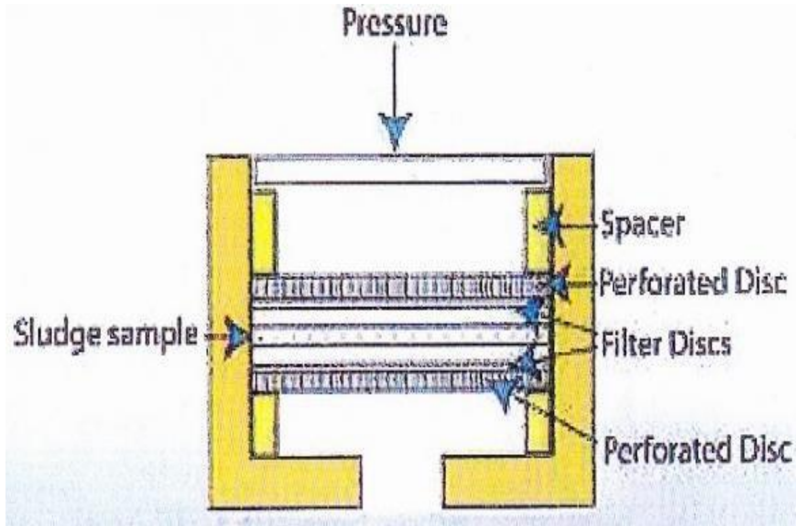


Figure 3.5: Schematic diagram of the bench press

The parameters that will be monitored are:

- Optimum polymer dose rate using the polymer consumption equation
- Cake dryness was obtained using a moisture analyser
- Strength of the floc was a visual observation based on how the cake secreted through the belts as pressure were applied.

3.5.2.1 Bench press procedure

This test method combines the process of flocculation with a mechanism for exerting pressure for a variable time on a sludge sample.

1. Select a sample volume which is enough to give a minimum 3 mm – 4 mm cake thickness after compression

2. This volume was selected by using a simple mathematical calculation presented in equation 8.

$$\mathbf{DS\ Content} = \frac{\pi r^2}{4} \times \mathbf{cake\ height} \times \mathbf{SS\ in\ cake} \qquad \textbf{(8)}$$

3. If a sludge sample is 0.5% solids concentration, the sample volume should be approximately 530 ml.

4. Adjustments of the solid's concentration were required since the bench press test can only hold a maximum volume of 400 ml.
5. The feed solids were adjusted for MSWWTPs A, B, and C due to the WAS's having a very low feed solids concentration, which would result in very thin cakes forming after compression.
6. The WAS's was adjusted by allowing it to stand overnight, then scooping the supernatant out. The aim was to achieve a feed solids concentration of 2 g/l.
7. The polymer solution was added until clear floc separation occurred.
8. The objective was to determine the point at which enough floc formation occurred to capture small sludge particles, which would otherwise pass straight through the filter fabric.
9. Optimum dosage would rarely exceed twice the dosage required for the beginning of floc formation.
10. A' pour' test was carried out; six pours from one beaker to another.
11. The sludge sample was then prepared in one beaker and agitated for 10 – 20 seconds to ensure that the polymer and sludge are mixed intimately.

The bench tester was assembled in the following sequence (Solids Technology International Limited, 2001):

12. The sealing ring (O-ring as supplied) was inserted into the Perspex cylinder onto the internal lip.
13. The brass perforated pressure plate was then inserted.
14. Filter fabric disc was then inserted with the smooth side towards the sludge.
15. The flocculated sludge sample was then poured, and the filtrate clarity observed.
16. Leveling of the drained sludge with the spatula was required to represent 'ploughing' to encourage free water removal. This action mimics the gravity drainage zone of the belt press.
17. The second filter fabric disk was inserted, followed by the second brass pressure plate.
18. Thereafter the upper sealing ring and Perspex spacer were inserted.
19. The Perspex cylinder assembly containing the sample was placed onto the center of the tester base plate, and the T-shaped handle was turned for the applied pressure to the sludge sample to be loaded via the Perspex spacer.
20. Hand pressure was applied by turning the T-shaped handle. A 0.2 Bar of pressure for 30

seconds was applied to simulate the first low-pressure stage of the belt press.

21. Thereafter, at approximately 5-second intervals the pressure was increased in steps of 0.2 Bar up to 2 Bar, total final pressure. This gave a total time under the pressure of approximately 1 minute and 15 seconds.

22. The visual quality of the filtrate was observed of the filtrate.

23. The pressure plates were then removed, and if any extrusion through the fabric occurred, it was noted.

24. The top filter fabric cloth was carefully peeled off, cake release at this stage was observed and noted by the ease of the cloth removal.

25. A clean separation of cake from the cloth was considered ideal conditions, sticky cake without significant extrusion indicated possible belt washing problems or low solids recovery.

26. The following details were noted, sample volume, feed solids concentration, dose rate for floc formation, dose rate for a clear separation of flocs/supernatant quality, dose rate required to secure clear supernatant if different.

27. The drainage time was recorded to drain free water through the filter fabric.

28. The final cake solids concentration was then achieved using a moisture analyser.

For these experimental runs, only one polymer type was used at one ‘water type’, FLOPAM 4650 dissolved into potable water. This was due to, on a small scale the effects of the two polymer types were negligent. This might be due to both being similar in terms of polymer and that the only difference was their charged cationicity.

3.8 Statistical analysis of experimental data

For the gravity drainage test, data analysis was used to check the reliability of the data obtained and to ensure that the conditions set for this experiment were statistically significant. Single-factor ANOVA and a T-test was performed on the gravity drainage experimental data. This was done to see if there was an implication when changing the polymer, polymer concentration and water types used. The confidence level for this experimental test results was 95 %, hence α = 0.05.

For the bench press results design expert was used to verify the interaction that was observed by the polymer dosage (ml), feed solids concentration (%), solids concentration in the cake (%), and the cake height (mm). Respond surface methodology-based Box-Behnken Design (BBD) is favoured to compute the relationship between the input and output variables. For these experimental runs, a three-factor two-level Box-Behnken Design (BBD) was used. This was due to this experiment having 3 variables, polymer dosage, cake height, and feed solids, at two levels that influenced the response or outcome. This method was used to statistically analyse the effect of the operating parameters and their interactions on the Belt filter press performance using the Stat-Ease Design Expert V 10.0.7 version. The parameters earlier mentioned were evaluated by observing the effect they have on solids concentration of the cake and, therefore, on the sludge dewatering procedure used for this study. The ranges used are presented in Table 3.5. Only two levels were required for the factors represented by codes -1 (low) and +1 (high).

Table 3.4: Factors in Box-Behnken experimental design

Factors	Variables	Levels used	
		Low	High
Polymer dosage (ml)	A	12 (-1)	16 (+1)
Cake height (mm)	B	4 (-1)	7 (+1)
Feed solids (mg/l)	C	1 (-1)	3 (+1)

After the selection of process operating variables and their ranges, experimental runs were conducted based on the BBD, which consisted of seventeen runs, in a random pattern. The randomization of experimental runs prevented that the conditions in one run influenced the conditions of the previous runs. Nor predicting the conditions in the subsequent runs. Randomization of experiments is essential for the interpretation of results and concluding the experiment in an accurate, unambiguous, and defendable manner.

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter covers the results of the drainage control experimental runs and the bench press used as well as the discussion thereof. The sludge dewater-ability was assessed by focusing on the gravity drainage zone of the full-scale belt filter press and the compression zone. Two polymer types were used, FLOPAM 4650 and 4800, at 0.2% and 0.3% concentration, respectively.

An experimental investigation was conducted to determine sludge dewatering efficiency by:

- Varying water types when the make-up of polymer- flocculant,
- Sludge conditioning and filterability using drainage control test,
- Sludge conditioning using the bench-scale press,

4.2 Sludge characteristics

In Table 4.1, the sludge characteristics are displayed for the four WWTP's used for this study. According to Oerke (2016), the volatile suspended solids (VSS) and feeds solids (FS) concentration of WAS are important sludge characterization parameters when obtaining its' dewaterability since both the FS and VSS indicate the type and amount of polymer required, previously discussed in Chapter 2.

Table 4.1: Sludge Characteristics of the four WWTPs

Parameters	Units	Plant A	Plant B	Plant C	Plant D
Total Suspended Solids (TSS)	mg/l	3903	9282	8512	7746
Volatile Suspended Solids (VSS)	mg/l	3230	7162	7162	7068
Sludge volume index (SVI)	ml/g	148	104	117	103
Feed solids (FS)	%	1.1	1.2	1.1	3.4

An increase in total suspended solids (TSS) will result in poor dewatering. The increased TSS created a thicker sludge due to more solids present, which reduced the amount of filtrate during the gravity drainage test and increased the flocculant consumption. According to Chapter 2 literature, by analyzing the sludge characteristics in Table 4.1, the best performing WWTP during the dewatering test should follow the following trend from best to worst: WWTP A, D, C, and B. The volatile suspended solids (VSS) for Plant A were found to be approximately 50 % lower than for the other Plants. According to Oerke (2016), the VSS for Plant A, after dewatering should produce a drier cake, followed by Plant B, D than C. This is due to WWTP A having a lower VSS as compared to WWTP B, C, and D. The feed solids % is the expected feed solids for WAS, which is generally between 0.4 % - 1.5 % (Severin & Grethlein, 1996). Plant D, however, has a feed solids content of 3.4 %. This could be due to the gravity thickening process before the sludge dewatering operation at the plant (Process Controller Operational Hand Book, 2016).

4.3 Effects of sludge characteristics on sludge dewatering

4.3.1 Effects of Volatile Suspended Solids (VSS)

Figure 4.1 shows the difference in VSS for the four WWTPs, the higher the VSS, the more difficult the dewatering. The solid concentration in the cake will be low, and the mechanical properties will be low as well. This will increase the flocculant consumption, or the amount of polymer required for flocculation. The sludge cake producing the highest solids concentration of 18% was found at a VSS of 3230 mg/l. The sludge cake producing the lowest solid's concentration of 13 % had a VSS of 7162 mg/l. It's suggested a thickening step needs to be added before the dewatering step to improve the dewatering step if a high VSS is found. Only WWTP D has a thickening step in place before dewatering, however, regardless of it, the VSS is still high at 7068 mg/l compared to WWTP A at 3230 mg/l, without a thickening step, which can be seen in Table 4.1 above.

4.3.2 Effects of Feed solids (FS)

The optimum polymer demand (OPD) for the CoCT sludge dewatering should be 3.5 – 4.5 kg/DTS for waste activated sludge (WAS) (SNF Floerger, 2016). The polymer consumption was calculated in kg polymer per ton of solids using the following equation:

$$\frac{\text{PD} \times \text{polymer}}{1000} \times \frac{1000}{\text{Sludge Flow Rate} \times \text{feed solids}} = \textbf{Polymer consumption} \qquad \textbf{(9)}$$

The feed solids concentration in the sludge plays a very important role when determining polymer consumption. The thicker the feed solids concentration the drier the dewatered cake concentration (Oerke, 2016). Polymer consumption is lowered by increased feed solids concentration. Table 4.2 presents the change in polymer consumption for FLOPAM 4650 at 0.2 %.

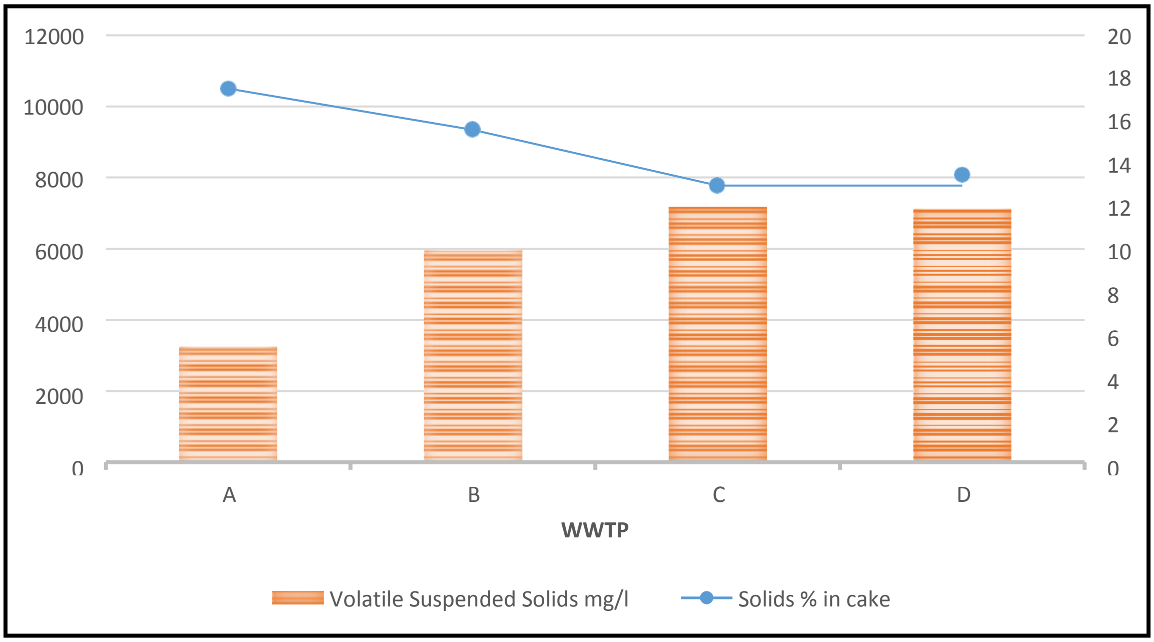


Figure 4.1: Volatile suspended solids effects on cake dryness

The change in polymer consumption for the rest of the experimental conditions is presented in Appendix A tables A.4.1 – A.4.4. These tables represents the results of the belt press tests conducted on all four WWTPs using the conditions stated below.

For this experimental run the conditions were:

- Sludge volume at 200 ml
- Feed solids for each run and each WWTP remained constant at approximately 2%.
- Two polymer types used, FLOPAM 4650 and FLOPAM 4650
- 0.2 % and 0.3 % concentration for each polymer.

These polymer concentrations was made up by diluting 0.5 g of polymer into 250 ml water for 0.2% concentration and 0.75 g of polymer diluted into 250 ml of water for 0.3 % concentration.

Table 4.2: Feed solids concentration effects on polymer consumption for each WWTP, FLOPAM 4650 at 0.2% concentration

Plant A	Solids in feed	**%**	1,87				
	Poly dosage	**ml**	12	13	14	15	16
	Poly consumption	**kg/DTS**	3.21	3.48	3.74	4.01	4.28
Plant B	Solids in feed	**%**	2,02				
	Poly dosage	**ml**	12	13	14	15	16
	Poly consumption	**kg/DTS**	2.79	3.22	3.47	3.71	3.96
Plant C	Solids in feed	**%**	2.13				
	Poly dosage	**ml**	13	14	15	16	17
	Poly consumption	**kg/DTS**	3.05	3.29	3.52	3.76	3.99
Plant D	Solids in feed	**%**	3.14				
	Poly dosage	**ml**	30	31	32	33	34
	Poly consumption	**kg/DTS**	4.78	4.94	5.10	5.25	2.41

Table 4.3: Feed solids concentration effects on polymer consumption for each WWTP, FLOPAM 4650 at 0.3 % concentration

Plant A	Solids in feed	**%**	1,87				
	Poly dosage	**ml**	12	13	14	15	16
	Poly consumption	**kg/DTS**	4.81	5.21	5.60	6.02	6.42
Plant B	Solids in feed	**%**	2,02				
	Poly dosage	**ml**	12	13	14	15	16
	Poly consumption	**kg/DTS**	4,46	4,83	5,20	5,57	5,94
Plant C	Solids in feed	**%**	2.13				
	Poly dosage	**ml**	13	14	15	16	17
	Poly consumption	**kg/DTS**	4,58	4,93	5,28	5,63	5,99
Plant D	Solids in feed	**%**	3.14				
	Poly dosage	**ml**	30	31	32	33	34
	Poly consumption	**kg/DTS**	7.17	7.40	7.64	7.88	8.12

4.4 Polymer dissolution water characteristics and their effects on sludge dewatering

Different dilution water for polymer activation was used to investigate the effects on sludge dewaterability. According to Kim (2015), the parameters to be considered when selecting polymer dilution water are conductivity, alkalinity, pH, E. coli, and TSS. Table 4.4 presents the results obtained for the parameters using different types of effluents. The MBR Treated Effluent was obtained from the permeate of the MBR Plant found at WWTP B. Treated effluent after filtration was obtained at WWTP A, after a filtration plant. Lastly final effluent before filtration was collected at WWTP A before the filtration plant.

Table 4.4: Parameters for dilution waters used for polymer activation

Parameters	Units	Recommended Value	MBR Treated Effluent	Treated Effluent after filtration	Final Treated Effluent before filtration
Conductivity	mS/m	< 1000	104	154	156
Alkalinity	mg/l $CaCO_3$	< 300	186	333	328
pH		6 < pH < 8	7,4	7,4	7,5
E. coli	1000 CFU per 100 ml	0	35	16	20
TSS	mg/l	< 5	6	24	10

The strength of the polymer solution is based on the treated effluent parameters since they have adverse effects on sludge dewatering (SNF Floerger n.d.). The effect of high conductivity of the dilution water for the polymer make-up decreases the dissolution speed and polymer solution viscosity. Alkalinity is a measure of water hardness and the recommended value for water used as polymer dilution water should be less than 300 mg/l $CaCO_3$. A higher than the recommended value would cause hydrolysis of the cationic polymers. This is because multi-valent ions hinder polymer activation. Therefore, soft water helps extend polymer chains faster and water with a hardness greater than 400 mg/l $CaCO_3$ would need a softner (Kim, 2019). Hard water is considered between 150 – 300 mg/l $CaCO_3$ and very hard water is considered above 300 mg/l

$CaCO_3$ (Ahn *et al.,* 2018). The pH is one of the most important factors when considering the dilution water used for polymer make-up. This is due to an acid or base act as a catalyst, that is, they greatly accelerate the degradation process. High pH will cause hydrolysis for cationic polymers. The Bacteria present in treated effluent or the E. coli, has a recommended value of 0 1000 CFU per 100 ml. Bacterial growth which will occur due to higher than the recommended E.coli value will produce a foul odour and will also cause rapid degradation of the polymer make-up solution. The total suspended solids (TSS) present in the treated effluent should be less than 5 mg/l. This is due to with the presence of solids in the dilution water, the polymer would react with these solids before the polymer solution is added to sludge. This would result in a weaker polymer make-up solution, which would result in an ineffective dewatering operation (Kim, 2019). As well as solid build, up in the make-up tank which would create skin and blockage of pumps and lines.

In Table 4.4 alkalinity for treated effluent before and after filtration was slightly higher, 333 and 328 mg/l $CaCO_3$ respectively, than the recommended value of less than 300 mg/l $CaCO_3$ compared to MBR effluent, 186 mg/l $CaCO_3$. The suspended solids for MBR effluent, treated effluent after filtration and treated effluent before filtration are also slightly higher, 6, 24 and 10 mg/l respectively, as well as the bacteria / E. coli, 35, 16 and 20 1000 CFU per 100 ml respectively. Therefore, degradation and hydrolysis of the flocculant mixture will occur for treated effluent before filtration and treated effluent after filtration. The results of the drainage control test will provide data of which the degradation has affected the filtration process. For treated effluent after filtration the amount of solids captured on the filter medium should be the lowest based on the effluents characteristics presented in Table 4.4. This is due to a weaker polymer make-up solution formed (SNF Floerger n.d.).

4.5 Drainage control test results

The gravity drainage test was conducted on the four WWTPs WAS, using FLOPAM 4650 and FLOPAM 4800 at a concentration of 0.2 % and 0.3 %. Four treated effluents were used for polymer dissolution. A representative sample of the sludge was collected and an analysis of the dry solids content (DS) of the sludge was conducted. The aim was to obtain the following results:

- The gravity drainage speed during the first 10 seconds
- The filtrate quality, by visual observation
- The efficiency of the polymer at low, optimum and high dosages and
- The effect of Specific Resistance to Filtration (SRF) on polymer dosage

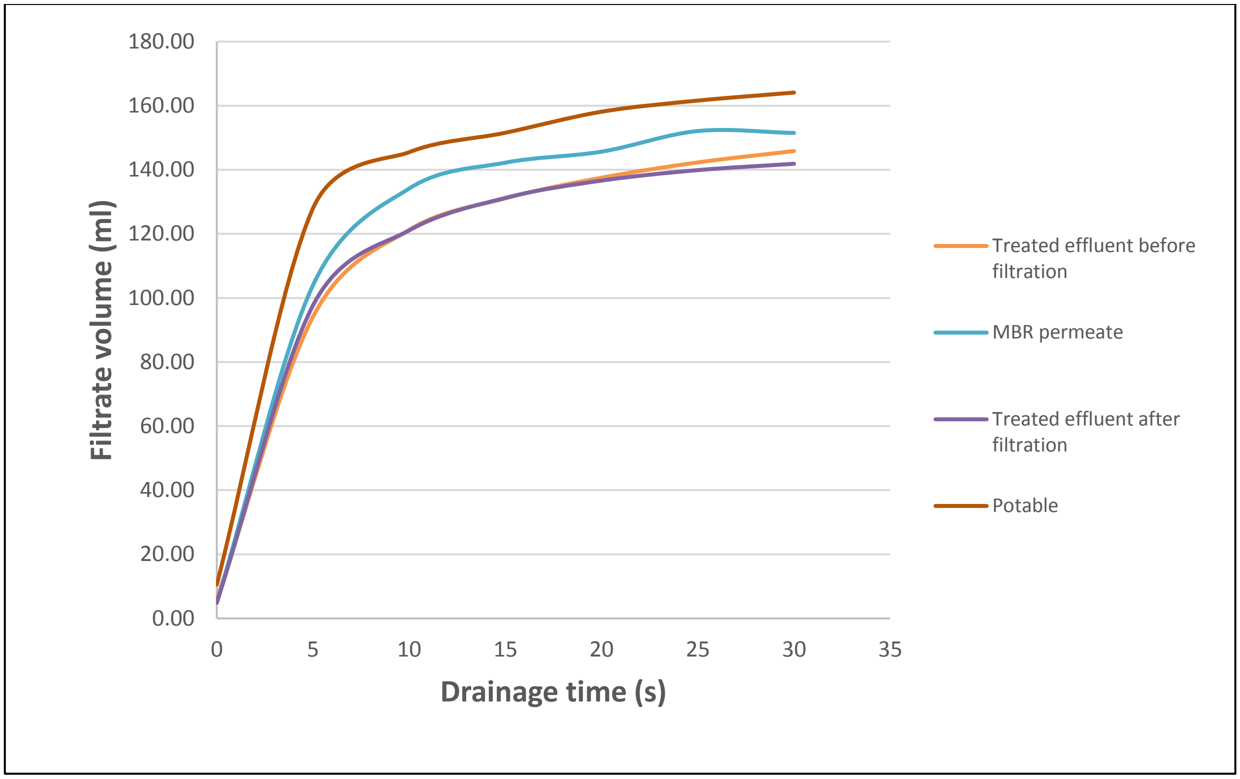
4.5.1 Gravity drainage during the first 10 seconds

The required polymer dosage differed for each dilution water used to make up the polymer solution, which can be seen in Figure 4.2. The MSWWTPs A, B, and C all followed a similar trend with the same volume drained. This is due to these plants all having similar sludge characteristics in terms of feed solids concentration (%). WWTP D drained at a much lower captured volume but with a higher polymer dosage. According to SNF Floeger n.d., the higher the feed solids concentration the more polymer required for sludge dewatering the slower the rate of gravity drainage due to an increased build-up of solids on the filter cloth.

Other than sludge characteristics, polymer characteristics such as charge density, the number of branches and the molecular weight greatly affects the performance of flocculation which in tern affects gravity drainage as well. In Figure 4.2 for potable water as polymer dilution water, the highest amount of filtrate was drained as compared to the other three effluents used. This is due to less ions present in potable water which can interfere with the flocs produced. The flocs produced were large and open, leaving behind majority of the solids and filtering through most of the water (Pinheiro *et al.*, 2010).

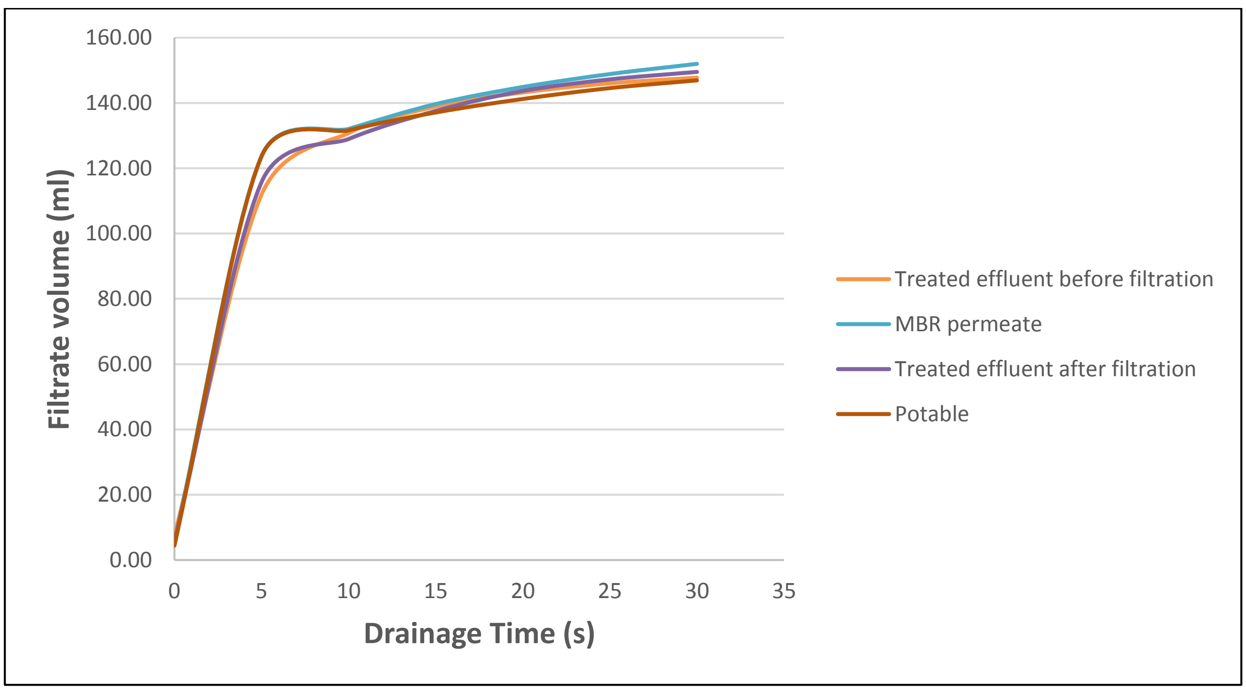
When comparing the drainage curves of both polymers, it was observed that FLOPAM 4800 required less polymer than FLOPAM 4650 for WWTPs A, B, and D. This could be due to FLOPAM 4800 having a cationicity of 80% and FLOPAM 4650 55 % (SNF Floerger n.d.) with a higher molecular weight. The higher the cationic charge the lower the polymer demand to establish sludge flocculation for dewatering. All water types produced similar trends of the drainage curves as observed by other researchers (Vaxelaire & Olivier, 2007, Charles. L, 2005). However, for WWTP D using FLOPAM 4800, the drainage curve had a wider gap in-between each “water type” graph.

The filtered volumes showed a distinctive difference with a lower filtrate volume when compared to the FLOPAM 4650 drainage curve. Previous work done by Vaxelaire & Olivier (2007) suggested that a higher molecular weight polymer had a lower released filtrate volume compared to a medium molecular weight polymer. The polymer with a high branched structure and with a high molecular weight significantly improves the drainage rate as compared to polymers with medium molecular weight and/or low branching. Therefore, the change in the polymers from FLOPAM 4560 to 4800 produced different filtered volumes. Hence, WWTP D performed the way it did with different “water types”.



180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Filtrate volume (ml)
0
5
10
15
20
25
30
35
Drainage time (s)
Treated effluent before filtration
MBR permeate
Treated effluent after filtration
Potable

(1)



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Filtrate volume (ml)
0
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10
15
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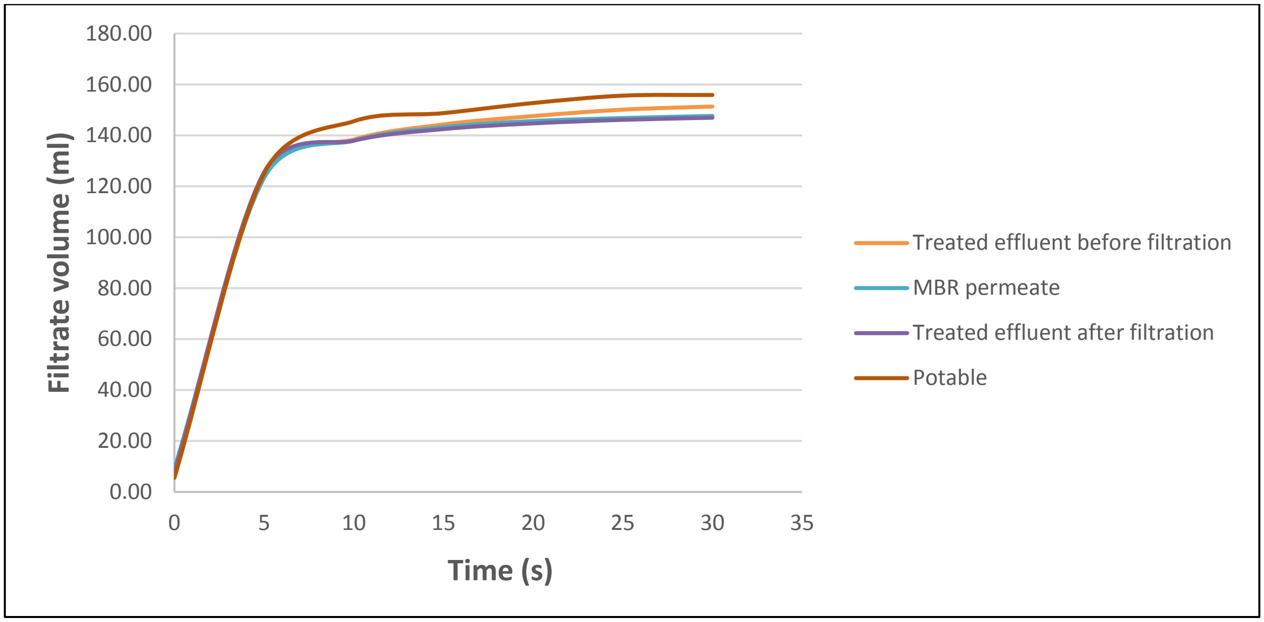
25
30
35
Drainage Time (s)
Treated effluent before filtration
MBR permeate
Treated effluent after filtration
Potable

(2)



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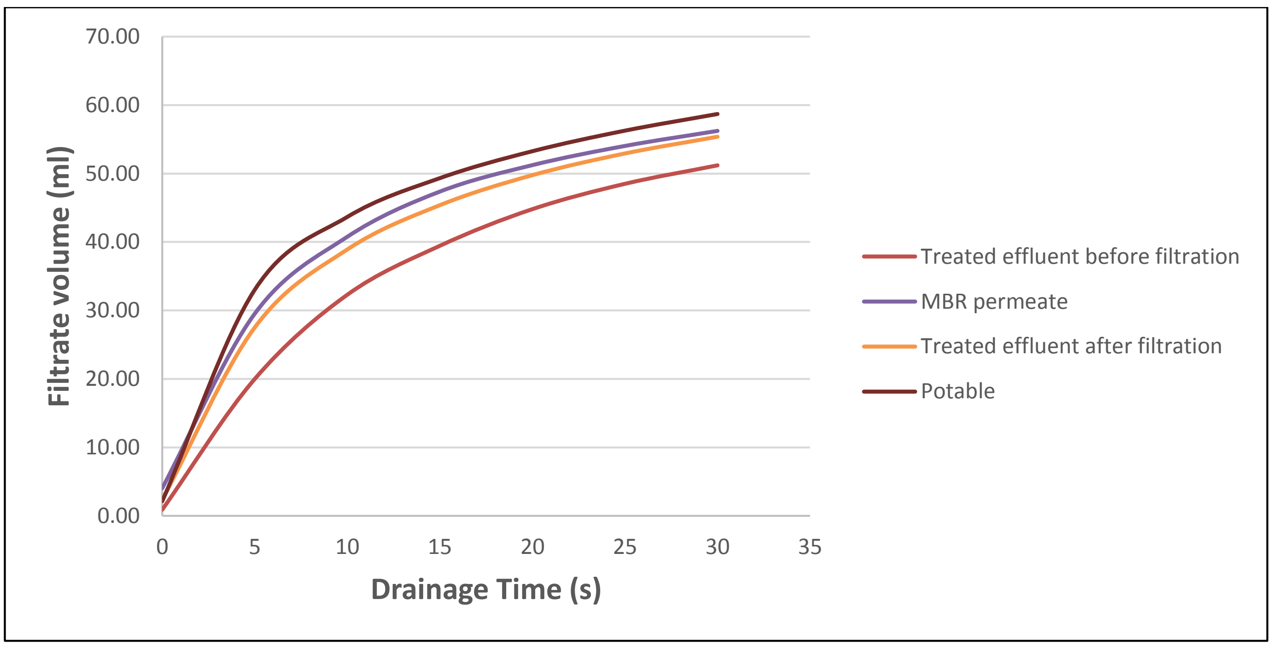
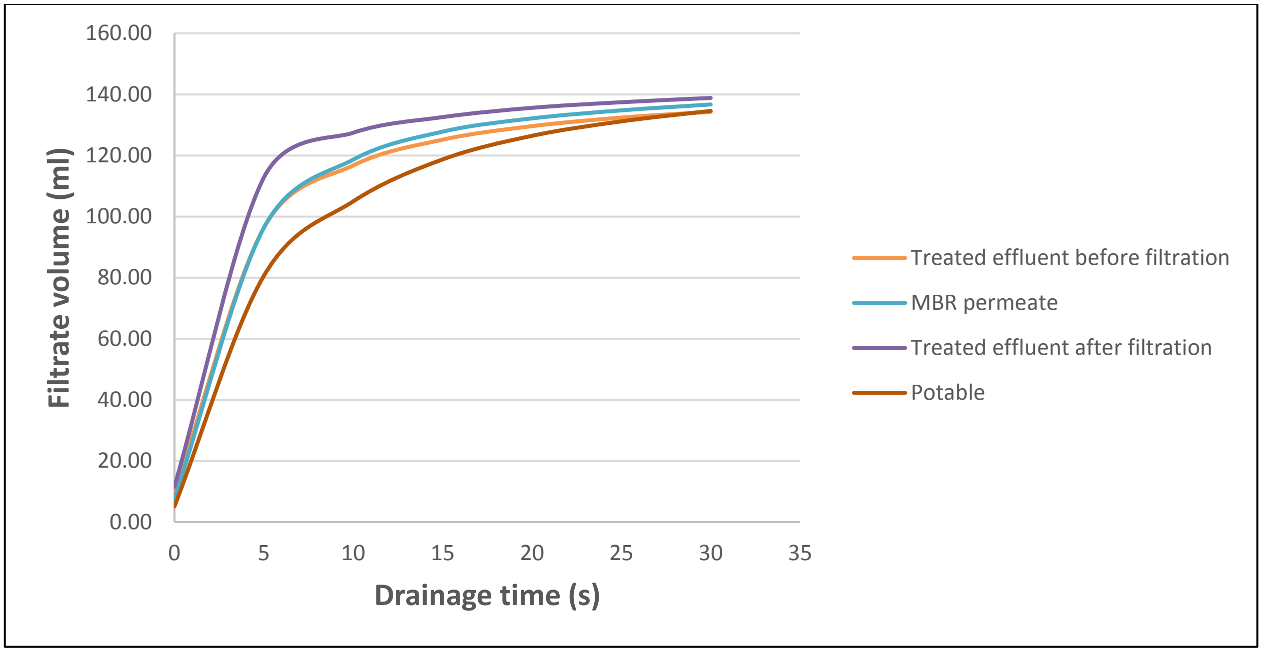


(4)

Figure 4.2: Drainage curves for FLOPAM 4650 with various polymer dilution waters (1) WWTP A, (2) WWTP B, (3) WWTP C, (4) WWTP D



160.00
140.00
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Filtrate volume (ml)
0
5
10
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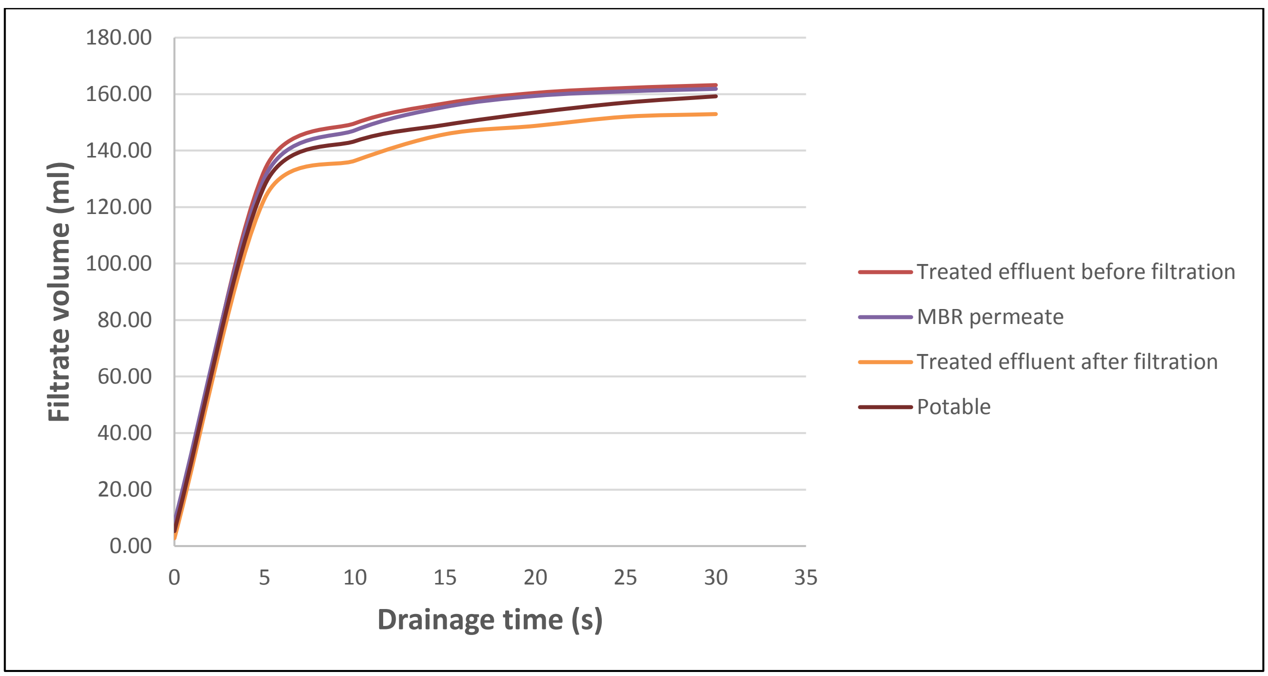
20
25
30
35
Drainage time (s)
Treated effluent before filtration
MBR permeate
Treated effluent after filtration
Potable

(1)



180.00
160.00
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80.00
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Filtrate volume (ml)
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5
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25
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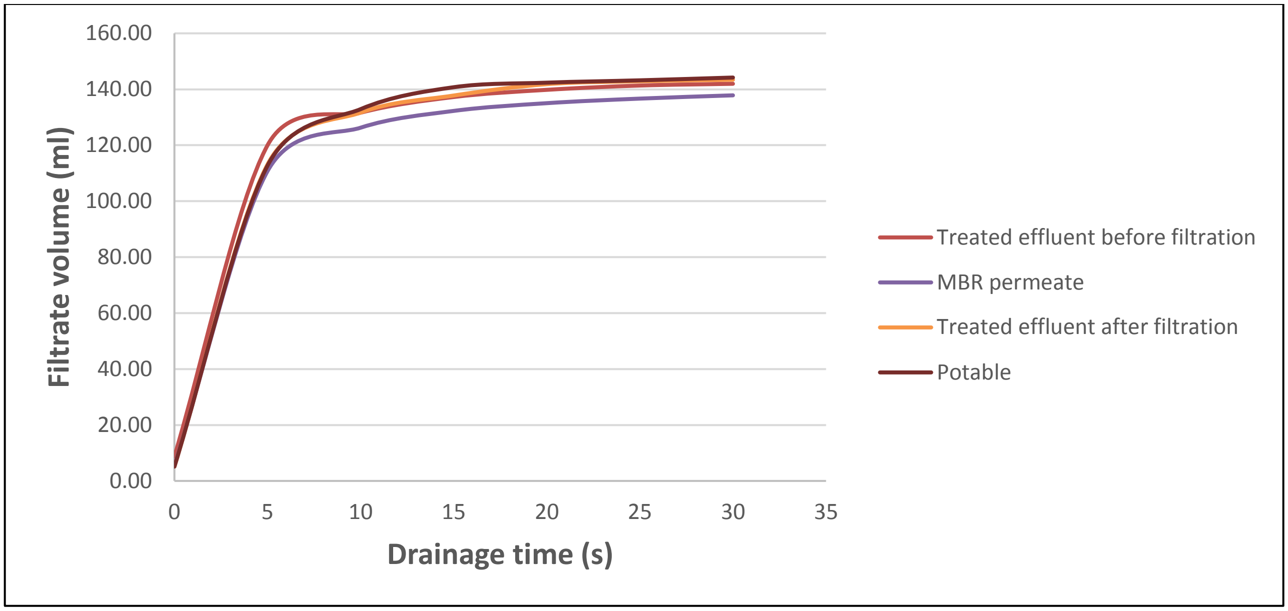
35
Drainage time (s)
Treated effluent before filtration
MBR permeate
Treated effluent after filtration
Potable

(2)



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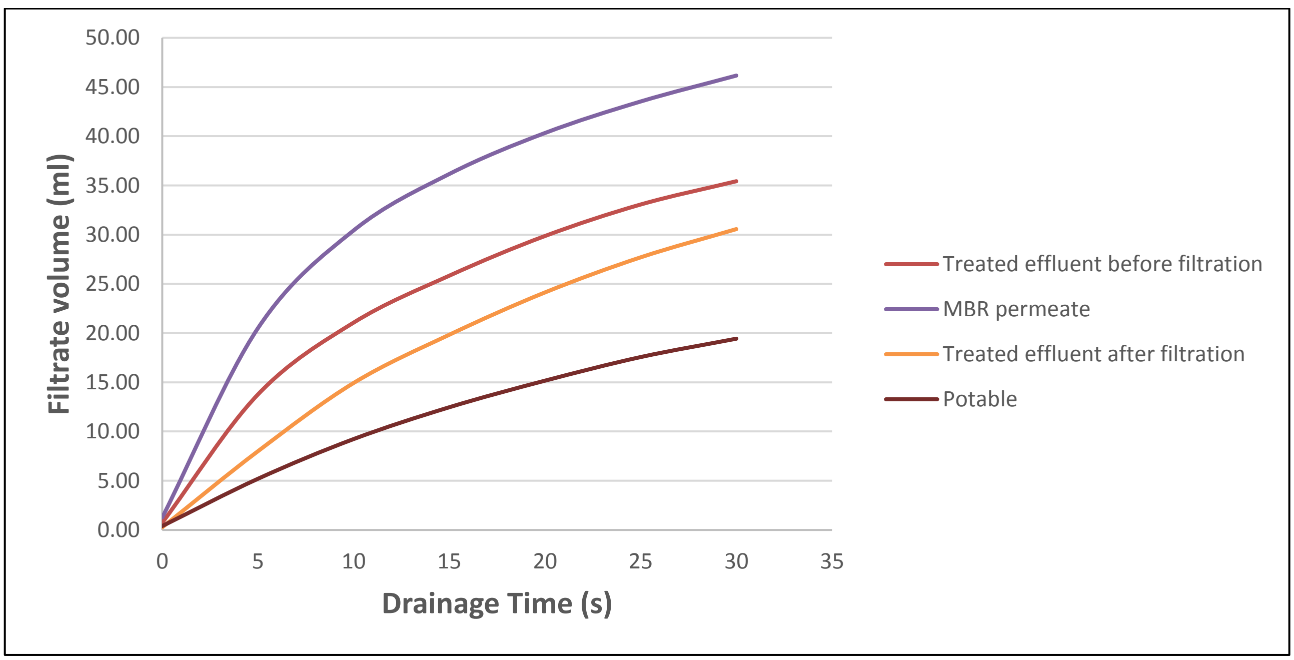


(4)

Figure 4.3: Drainage curves for FLOPAM 4800 with various polymer dilution water are (1) WWTP A, (2) WWTP B, (3) WWTP C, (4) WWTP

Table 4.5: Experimental data for the gravity drainage volume at

T = 10 seconds for FLOPAM 4650

Time (seconds)	WWTP	Volume (ml)	Dilution water
10	A	157	Treated effluent before filtration
10	B	132	MBR effluent
10	C	150	MBR effluent
10	D	56	Treated effluent before filtration

The best flocculant is the one that drains the most water in minimum time, the more water is drained the less sticky and packed the solid particles which intern allows water to pass through them. However, the quality of the filtrate also needs to be considered. Clear filtrate indicated that solid particles were binding well during the flocculation step. Therefore, fewer solid particles are filtered through the filter medium. Within the first 10 seconds of the drainage test, WWTP A had the highest drained volume of 157 ml with treated effluent before filtration as polymer make-up water. Huang et al. (1979) stated that hard water used as polymer dissolution water produced better results for sludge filterability compared to softer water, which concurs with these results. Treated effluent before filtration is considered hard water due to the parameters presented in Table 4.4.

Table 4.6: Summarized experimental data for the gravity drainage volume at

T = 10 seconds for FLOPAM 4800

Time (seconds)	WWTP	Volume (ml)	Dilution water
10	A	135	Treated effluent before filtration
10	B	150	Treated effluent before filtration
10	C	140	Treated effluent after filtration
10	D	36	MBR effluent

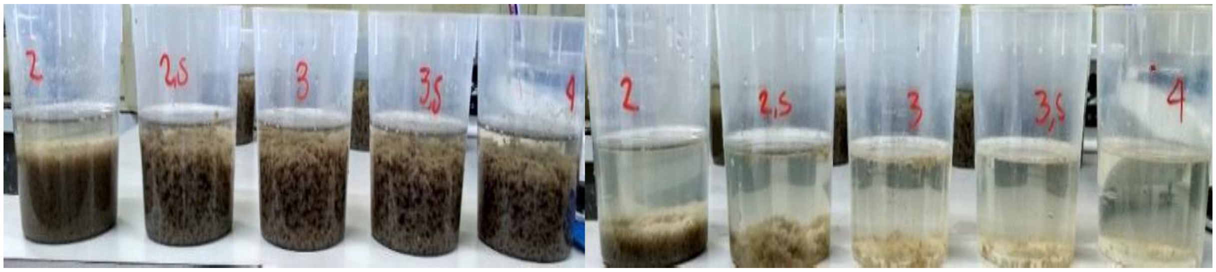
Table 4.6 showed that using FLOPAM 4800, WWTP B generated the highest gravity drained volume of 150 ml within the first 10 seconds of the experimental run. This was achieved with treated effluent before filtration at a polymer dosage of 2 ml. When the polymer type changed from FLOPAM 4650 to FLOPAM 4800 a difference in results was observed. The significant difference was determined with “water types” at the same polymer dosage and different polymers using Anova (FLOPAM 4650 (treated effluent before filtration) p-value = 0.9241 and FLOPAM 4800 (MBR permeate) p-value = 0.7575). WWTPs A and C, reduced when changing the polymer used. This is due to a higher molecular weight polymer producing sticky cakes and this results in a reduced flow of water through the formed cake (SNF Floerger, n.d). For filtration, the required molecular weight polymer is low to medium to obtain good drainage and flocculation.

4.5.2 The filtrate quality

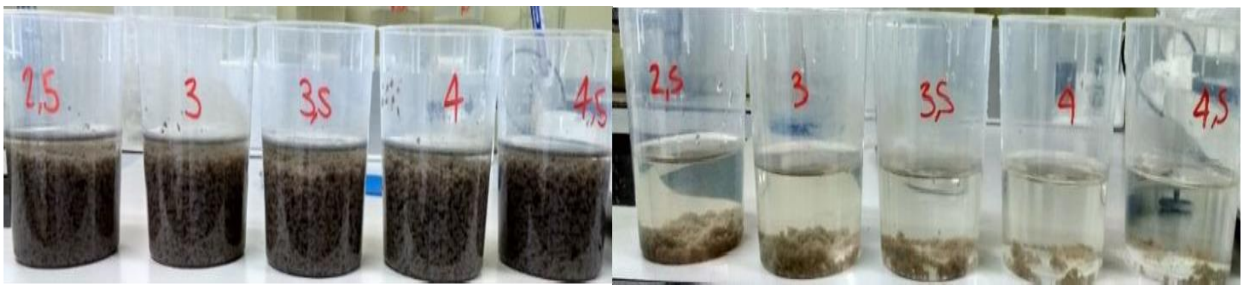
Photograph 4.1 visually shows the gravity drainage test before and after, with FLOPAM 4650 and MBR effluent as polymer dilution water. All images showed that as the polymer dose rate increased the number of solids that passed through the filter cloth reduced. Each WWTPs required different initial polymer dosage. WWTP A, Figure 1, had an initial polymer dosage of 1ml, WWTP B, Figure 2, 2 ml, WWTP C, Figure 3, 2.5 ml, and lastly WWTP D, Figure 4, required 12 ml initial polymer dosage. This was due to different sludge characteristics in terms of feed solids concentration. Where WWTP D had the highest feed solids therefore it required the highest polymer dosage for flocculation to occur.

(1)

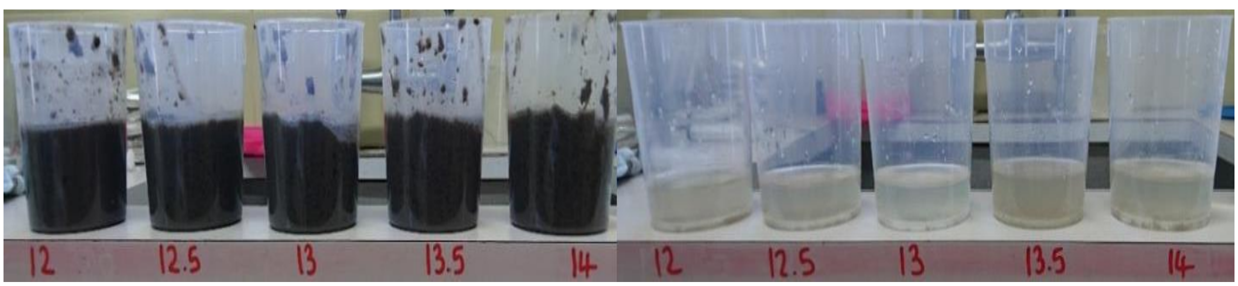
Cape Peninsula University of Technology



(2)



(3)



(4)

Photograph 4.1: Visual Observation of the filtrate quality after drainage control test, (1) WWTP A, (2) WWTP B, (3) WWTP C and (4) WWTP D

In conclusion, the sludge that had the highest feed solids concentration required more polymer for efficient flocculation and gravity drainage. This is an important parameter that needs to be considered when looking at a sludge dewatering operation. They may have similar characteristics, but they will still perform differently.

4.5.3 Obtaining the minimum, optimum and maximum polymer demand

The minimum, optimum, and maximum polymer dosage was obtained in a screening Jar test before the experimental runs were conducted. The results are presented in Table 4.7 for FLOPAM 4650.

Table 4.7: Minimum, Optimum and Over-dose Polymer Demand (PD) for WWTP's

WWTP	Minimum Polymer Demand (ml)	Optimum Polymer Demand (ml)	Overdosed Polymer Demand(ml)
Plant A	1	2	3
Plant B	2	3	4
Plant C	2.5	3.5	4.5
Plant D	12	13	14

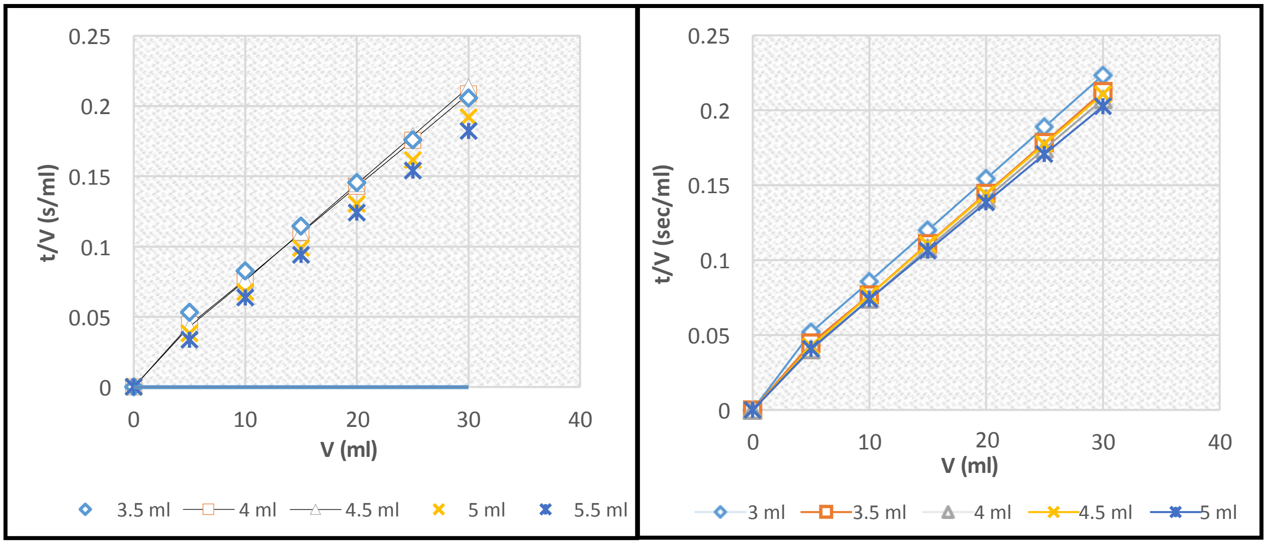
The minimum dosage occurred when the minimum polymer was added to the sludge when the flocs start to form as seen in Photograph 4.1. The optimum polymer demand (OPD) was obtained when bigger flocs and a clear separation of liquid and solids were observed. After the addition of an additional 1ml after the optimum PD was determined, overdosage occurred. Overdosing is represented as the final polymer dosage, which must be conducted during the screening test to obtain the optimum dosage. The optimum dosage is the dosage that would generally be used when the lab-scale tests are transferred to full-scale.

4.5.4 The effect of specific resistance of filtration (SRF) on polymer dosage

To obtain the SRF, a few assumptions were required (Qi et al., 2011). The results for SRF can be found in Appendix B:

- The pressure was constant at atmospheric pressure (101.325 kPa)
- The viscosity of the filtered liquid was water ($\mu = 8.90 \times 10 - 4$ Pa·s)
- C value is constant (0.021, g/ml)

At the filtration stage of the dewatering operation, the average specific resistance to filtration was constant; a plot of the inverse flux (t/V) against the filtrate volume (V) was linear (Qi et al., 2011). This is shown in Figure 4.4.



(1) **(2)**

Figure 4.4: Overall dewatering curves for sludge conditioned by (1) FLOPAM 4650, (2) FLOPAM 4800, and using wash water for polymer make-up

From the inverse flux versus volume graph, a constant value b was found by obtaining the slope of the line which can be seen in Tables 4.8 and 4.9. For FLOPAM 4650 the b values obtained are 0.0072, 0.0071, 0.0071, 0.0065 and 0.0062 sec/ml^2, for the polymer dosages of 3 to 5 ml. The SRF was then calculated and is represented in Tables 4.8 and 4.9 as well. Details of these calculations are found in Appendix B. The conditions for the results were, treated effluent before filtration as polymer make-up water for WWTP A.

Table 4.8: SRF values for FLOPAM 4650 for WWTP A

Polymer dosage (ml)	3	3.5	4	4.5	5
b values $(\mathrm{sec/ml^2})$	0,0072	0,0071	0,0071	0,0065	0,0062
SRF $(\mathrm{sec^2/g})$	$3\mathrm{x}10^5$	$3\mathrm{x}10^5$	$3\mathrm{x}10^5$	$3\mathrm{x}10^5$	$3\mathrm{x}10^5$

Table 4.9: SRF values for FLOPAM 4800 for WWTP A

Polymer dosage (ml)	3	3.5	4	4.5	5
b values $(\mathrm{sec/ml^2})$	0,0072	0,0069	0,0068	0,0069	0,0067
SRF $(\mathrm{sec^2/g})$	$3\mathrm{x}10^5$	$3\mathrm{x}10^5$	$3\mathrm{x}10^5$	$3\mathrm{x}10^5$	$3\mathrm{x}10^5$

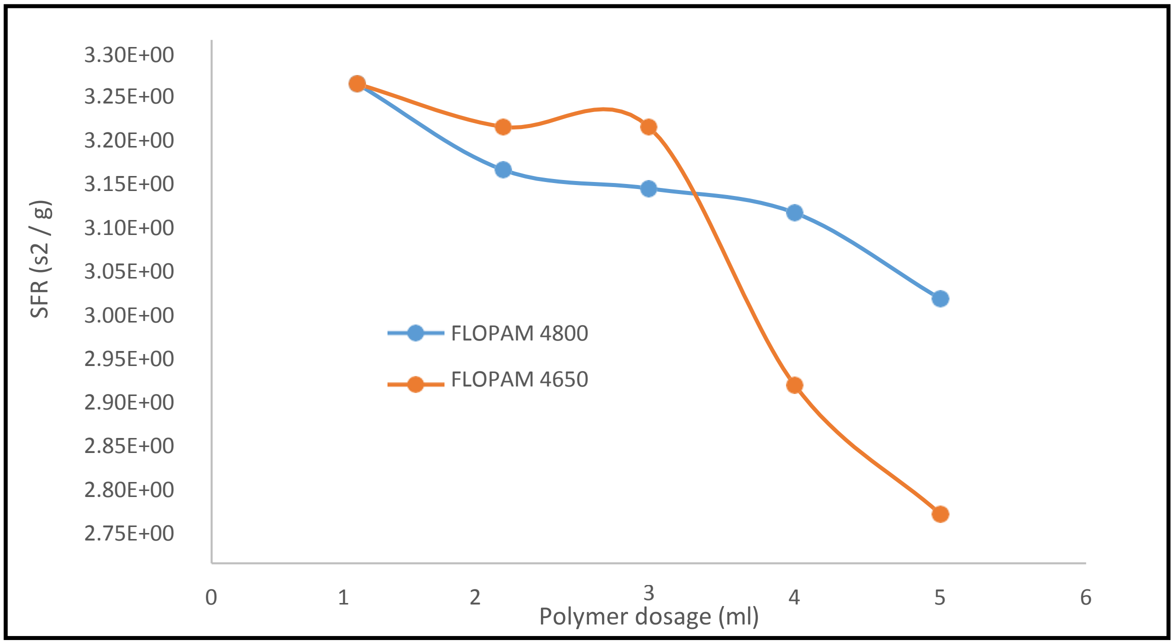


Figure 4.5: The Effect of SRF on polymer dosage for FLOPAM 4650 and FLOPAM 4800 with treated effluent before filtration as polymer dilution water

It was observed that a change in polymer, from FLOPAM 4650 to FLOPAM 4800, and polymer dosage, from 1 ml to 5 ml, in Figure 4.5, influenced the SRF at the condition represented in Tables 4.8 and 4.9. The SRF decreased with an increase of polymer dosage which agrees with previous authors (Sanin et al., 2011). However, the change in SRF is very small. Therefore, an assumption will be made that because the same sludge type was used (WAS) and that the main influencing parameter, feed solids concentration, remained constant for three or the four WWTPs, the SRF will be the same. Previous work conducted on obtaining the SRF values, various sludge types was used such as primary sludge, digested sludge, etc. Therefore, the SRF values obtained differed largely. However, for this study only WAS was used which explains the nearly constant SRF values obtained.

4.6 Lab-scale belt press results

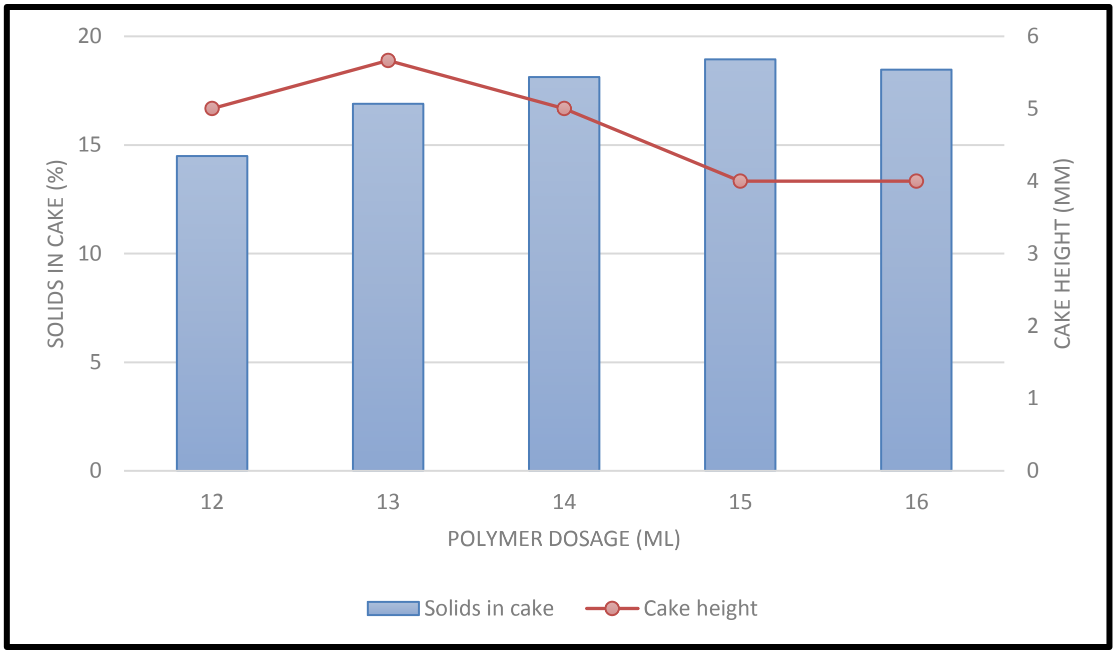
The bench press experimental runs show the interaction of polymer dosage on cake height formed after dewatering and solids concentration. The following key parameters were discussed in this section:

- Effects of polymer dosage on cake height and solids concentration of the cake
- Visual observation of cake height and filtrate quality

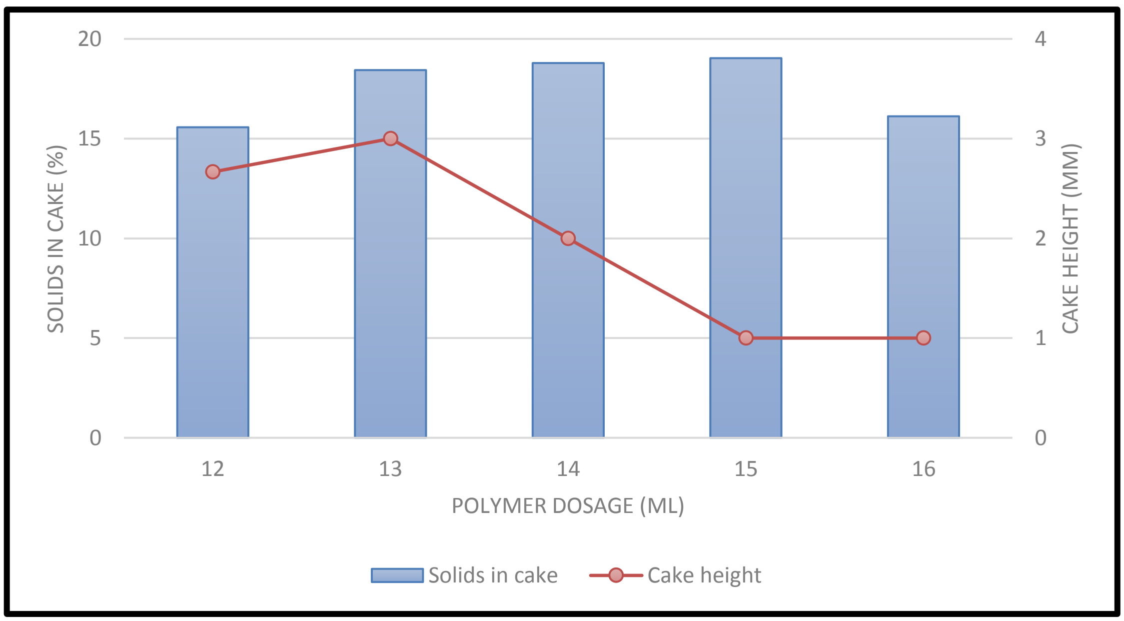
4.6.1 Effects of polymer dosage on cake height and solids concentration

Figure 4.6 represents the solids in the cake and cake height for all four WWTP. An increase in polymer dosage decreased the cake height, seen in Figure 4.6 for WWTP A when the polymer dosage increased from 13 ml to 14 ml, the cake height decreased from 6 mm to 5 mm. This decrease is demonstrated in Figure 2.10 in Chapter 2. A directly proportional correlation between the sludge cake height and solid concentration was observed. In Figure 4.6, when the cake height decreased, the optimum polymer dosage was achieved, for WWTP A the optimal was at a polymer dosage of 13 ml, for WWTP B at 13 ml, for WWTP C at 14 ml and for WWTP D at 31 ml. Therefore, for WWTP A, the optimum dosage obtained was 5.21 kg/DTS using a 400 ml sludge sample. WWTP B OPD at 4.83 kg/DTS, WWTP C OPD at 4.93 kg/DTS and WWTP D OPD at 10.67 kg/DTS.

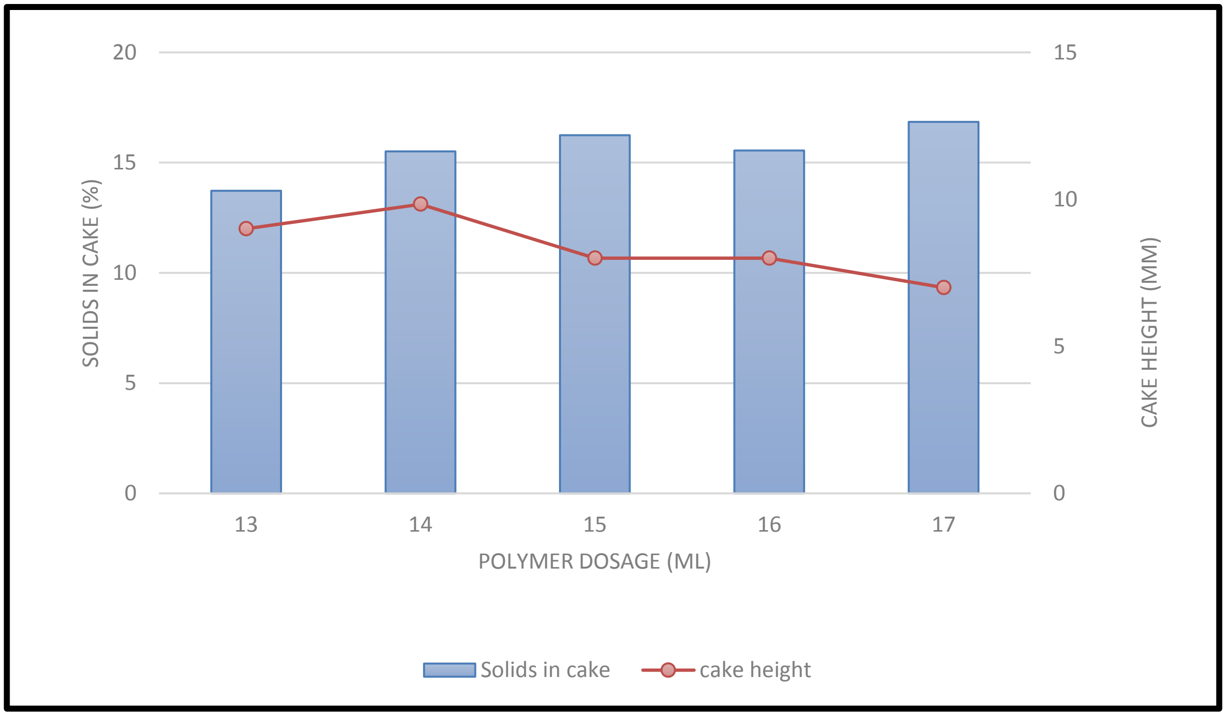
All the WWTP followed a similar trend other than WWTP D. The optimal polymer dosage for Plant D was attained at 10.67 kg/DTS. The reason for the very high amount of polymer required for flocculation for Plant D is due to the sludge having a high feed solid concentration. The more solids found in the sludge sample the more polymer required for flocculation to occur.


20
15
10
5
0
6
5
4
3
2
1
0
SOLIDS IN CAKE (%)
CAKE HEIGHT (MM)
12
13
14
15
16
POLYMER DOSAGE (ML)
Solids in cake
Cake height

(1)


20
15
10
5
0
4
3
2
1
0
SOLIDS IN CAKE (%)
CAKE HEIGHT (MM)
12
13
14
15
16
POLYMER DOSAGE (ML)
Solids in cake
Cake height

(2)



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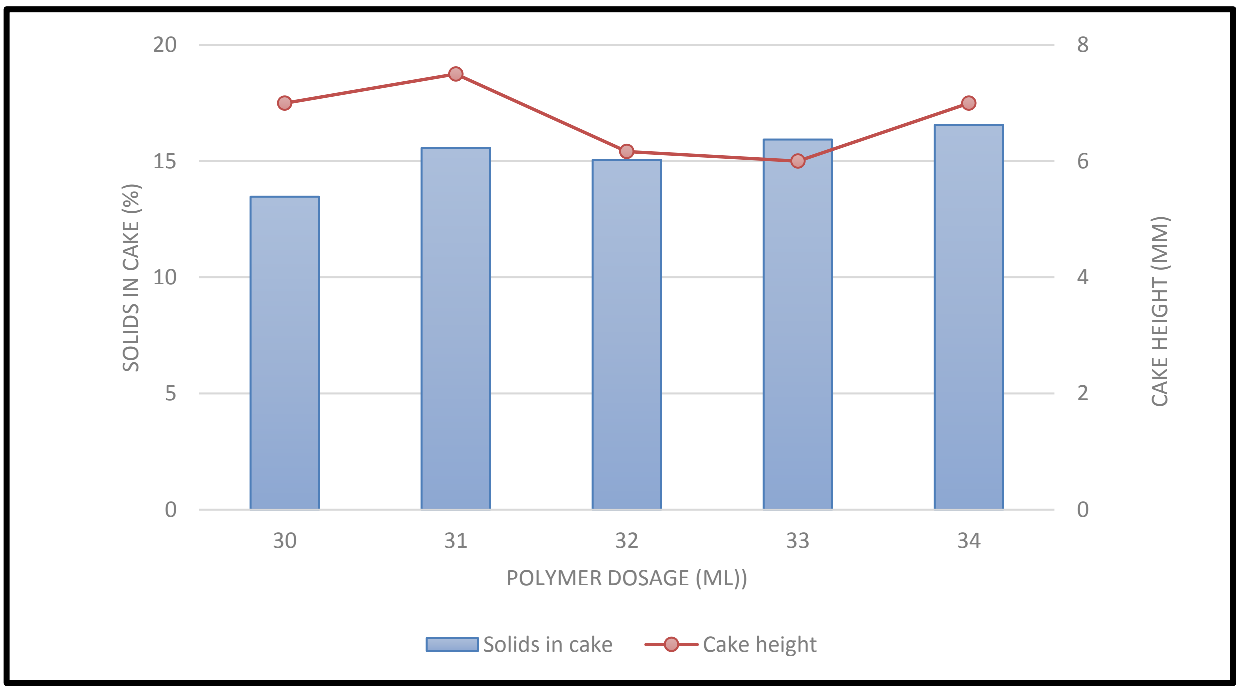


(4)

Figure 4.6: Influence polymer dosage have on cake height and sludge dryness: (1) WWTP A, (2) WWTP B, (3) WWTP C, (4) WWTP D

Table 4.10: The effect of feed solids on polymer dosage, cake height, and solids in cake

Std	Runs	Polymer dosage (ml)	Cake height (mm)	Feed solids (%)	Solids in cake (%)
5	1	12	5,5	1	4
1	2	12	4	2	11
6	3	16	5,5	1	4
8	4	16	5,5	3	12
4	5	16	7	2	6
3	6	12	7	2	6
9	7	14	4	1	6
11	8	14	4	3	17
13	9	14	5,5	2	8
2	10	16	4	2	11
12	11	14	7	3	10
10	12	14	7	1	3
17	13	14	5,5	2	8
16	14	14	5,5	2	8
7	15	12	5,5	3	12
14	16	14	5,5	2	8
15	17	14	5,5	2	8

Design expert 10.0.7 was used to find the interaction between solids in the cake, cake height, and feed solids. The experimental runs in Table 4.10 were used to investigate parameter interactions.

4.6.2 Development of the sludge dewatering model in terms of solids in cake

In Table 4.10, the interaction of polymer dosage, cake height and feed solids concentration as the three factors used which should have affected the solids concentration in the cake did not contribute to the model as predicted initially. This was shown by interaction graphs populated by Design Expert of those parameters and was omitted due to there not existing a statically significance. These figures are found in Appendix D, Figures D.1 – D.4. The perturbation plot observed in Figure D.1 between polymer dosing, cake height and feed solids concentration on solids concentration in the cake populated a horizontal straight line. This shows that there is no significant relationship between the three factors polymer dosing (A), cake height (B) and feed solids concentration (C) to the solid's concentration in the cake. In Figure D.2, the interaction plot of polymer dosing (A) and cake height (B), another straight line was observed. Both Figures D.3 and D.4 contour plots was able to be used to discuss the relationship that exists between factors A, B, C on the solid's concentration in the cake. Therefore, an assumption can be made at this point that all three factors does not have an effect on the solid's concentration in the cake simultaneously but rather individually instead. The only interaction that contributed to this model or that was significant was the cake height (B) and feed solids concentration (C) on the solids in cake concentration.

The Anova results found in Table 4.11 obtained by Design Expert for the sludge dewatering quadratic model presents the analysis of variance and shows the significant model term affecting sludge dewatering. Polymer dosage (A) was removed since it had no significant contribution to the model. The R^2 and adjusted R^2 values are also presented below Table 4.11 which indicates the degree of fit and is defined as the ratio of the explained variation to the total variation. The suggested R^2 value should be at least 0.8 to obtain a good fit for the model. Therefore, for this experimental run, the quadratic model was a good fit, $R^{2,}$ and R^2 adjusted is higher than 0.8. The model was significantly shown by the very low P-value lower than 0.05. A p-value lower than 0.05 indicates that the model is statistically significant at 95 % confidence.

Table 4.11: Anova results for sludge dewatering properties

ANOVA for Response Surface Quadratic model						
Source	**Sum of squares**	**df**	**Mean square**	**F value**	**P – value**	
Model	200.88	4	50,22	602,65	< 0,0001	significant
A	50,00	1	50,00	600,00	< 0,0001	
B	144.50	1	144,50	1734,00	< 0,0001	
AB	4,00	1	4,00	48,00	< 0,0001	
A^2	2,38	1	2,38	28,59	0,0002	
Residual	1,00	12	0,083			
Lack of fit	1,00	4	0,25			
Pure error	0,000	8	0,000			
Corrected total	201,88	16				

R^2 = 0.9950; adjusted R^2 = 0.9934 was obtained from Design Expert.

A represents cake height and B feed solids. AB represents the interaction between cake height and feed solids. A^2 is the quadratic effect of cake height

The final model, in terms of coded factors, is presented in Equation 10:

$$solids\ in\ cake = +8{,}00 - 2{,}50 * A + 4{,}25 * B - 1{,}00 * AB + 0{,}75 * A^2 \qquad \textbf{(10)}$$

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels of the factors are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

The equation in terms of actual factors:

$$solids\ in\ cake = +11{,}41667 - 4{,}00000 * cake\ height + 7{,}91667 * feed\ solids - 0{,}66667 * cake\ height * feed\ solids + 0{,}33333 * cake\ height^2 \qquad \textbf{(11)}$$

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor.

This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the centre of the design space.

The equations above a positive sign before a term indicates an increasing effect, while a negative sign indicates a decreasing effect on solids concentration in the cake

4.6.2.1 Validation of the sludge dewatering model

The validation of the sludge dewatering model was assessed by the actual and predicted values of the cake height and feed solids concentration shown in Figure 4.7. This figure indicates that this model was adequate for the prediction of the solid's concentration in the cake. This is due to the predicted values being relatively close to the observed solids concentration in the cake. The R^2 value, presented earlier, also explained that the model was adequate based on its value of 0.995, which indicates that the model explains 99.5% variation.

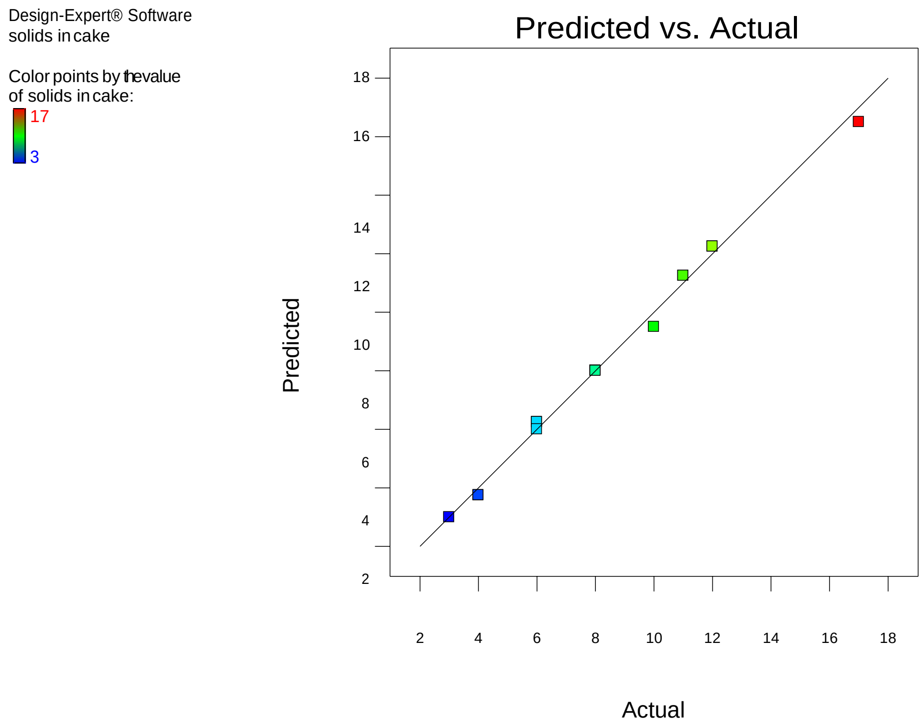


Figure 4.7: Predicted solid concentration in the cake vs actual solids concentration

4.6.2.2 Effect of process parameters on solids concentration in the cake

It has been shown that the polymer dosage contributes no significance to the solid's concentration in the cake as seen in Figures D.1 – D.2 in Appendix D; therefore, it will not be discussed. The reason behind predicting the solids concentration in the cake is to develop a model to select an appropriate range for process optimization.

The factor that significantly affects the solids concentration of the cake appears to be the feed solids (B) of the sludge. This is indicated by the model, Equation (10) above, where an increase in feed solids (B) increases solids concentration in the cake by 4.25. The second factor is the cake height (A) observed by the model, Equation (10) above, which decreased the solids in the cake by 2.5. The second relationship between cake height and solids in the cake does not explain what the actual experiment concluded, which was that an increase in cake height increased the solids concentration in the cake. However, when the feed solids increased an increase in solids of the cake was observed as stated above for factor feed solids (B), in Equation 10. The interaction between factor (AB) cake height and feed solids reduced the solids concentration by 1. According to the output of the models obtained from Design Expert, Equations 10 and 11, this interaction had the lowest significant effect on the solid's concentration of the cake.

Figure 4.8 presents a perturbation plot highlighting the effect of the feed's solids and cake height on the solid's concentration in the cake. The perturbation plot permits to compare the effect of all the factors at a certain point in the design space. This type of plot is like one factor at time experimentation and therefore does not show the effect of interactions.

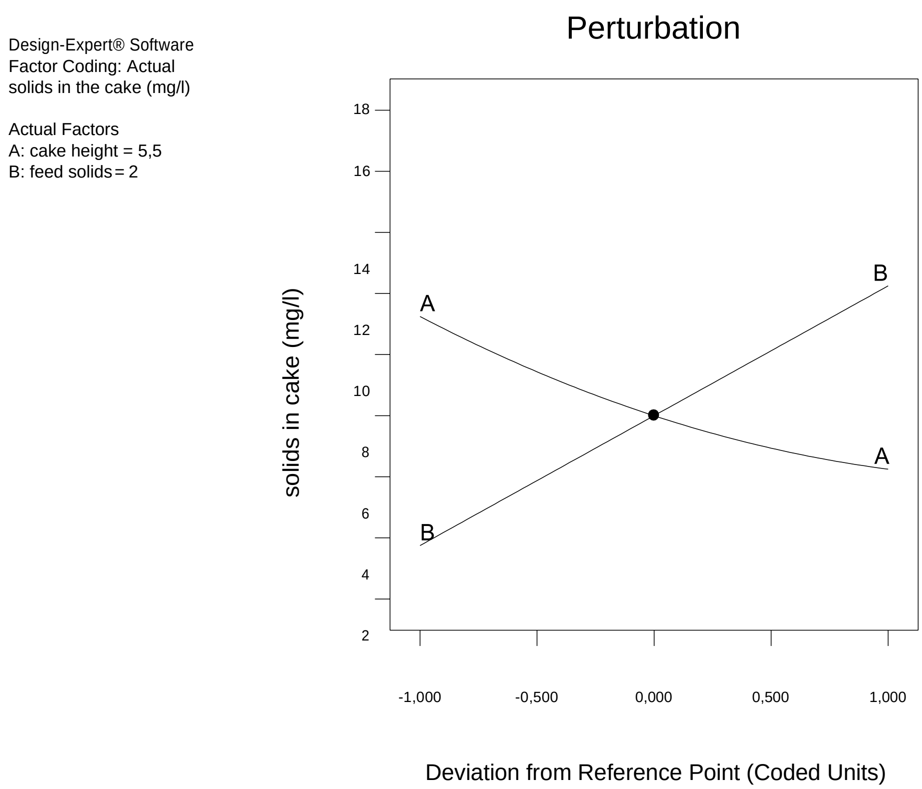


Figure 4.8: Perturbation plot for feed solids concentration and cake height

The significant interaction between feed solids concentration and cake height affecting the solids concentration in the cake is presented in Figure 4.9. The 3-D and 2-D contour plots shown in Figures 4.10 and 4.11, respectively, highlights the positive influence of increasing both the feed solids concentration and the cake height. In Figure 4.11 the 3D contour plot, the interaction shows that the solids concentration increases with an increase in feed solids. When the cake height was 3 mm the solids in the cake resulted in 16.5 mg/l. This is exactly the trend that should be followed in sludge dewatering. However, when the cake height reduces an increase in solids in the cake is found. This is not the trend that was followed for the experimental test, the opposite was observed.

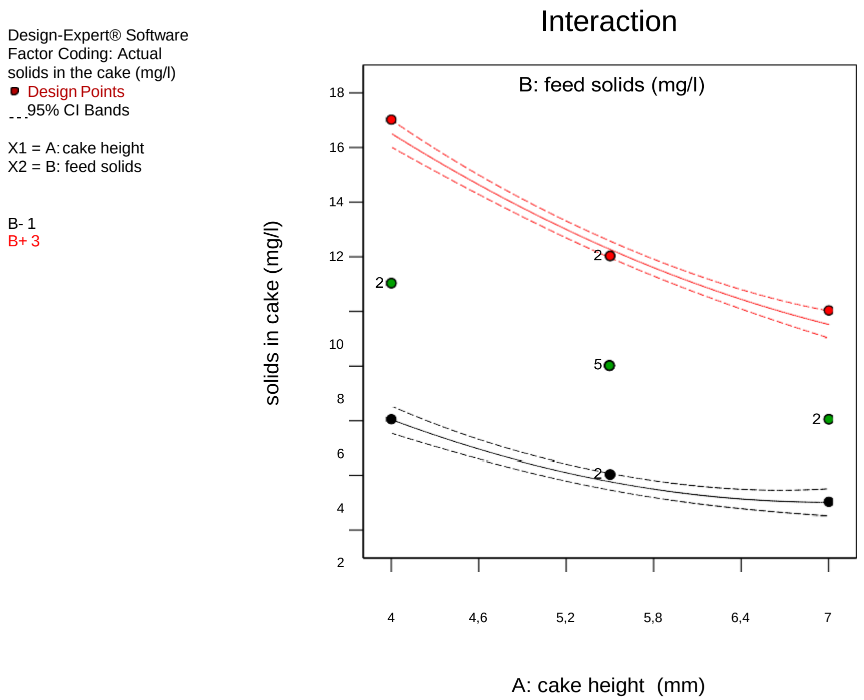


Figure 4.9: Interaction plot for the effect of cake height and solids in cake concentration

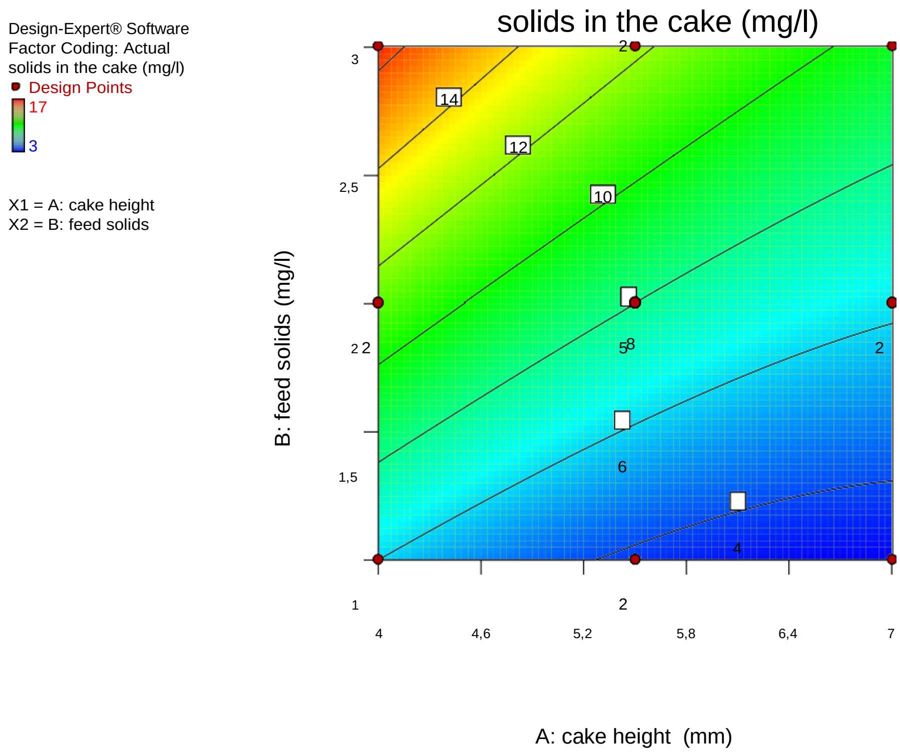


Figure 4.10: 2D surface contour plot showing the effect of cake height and feed solids on the solids in cake concentration

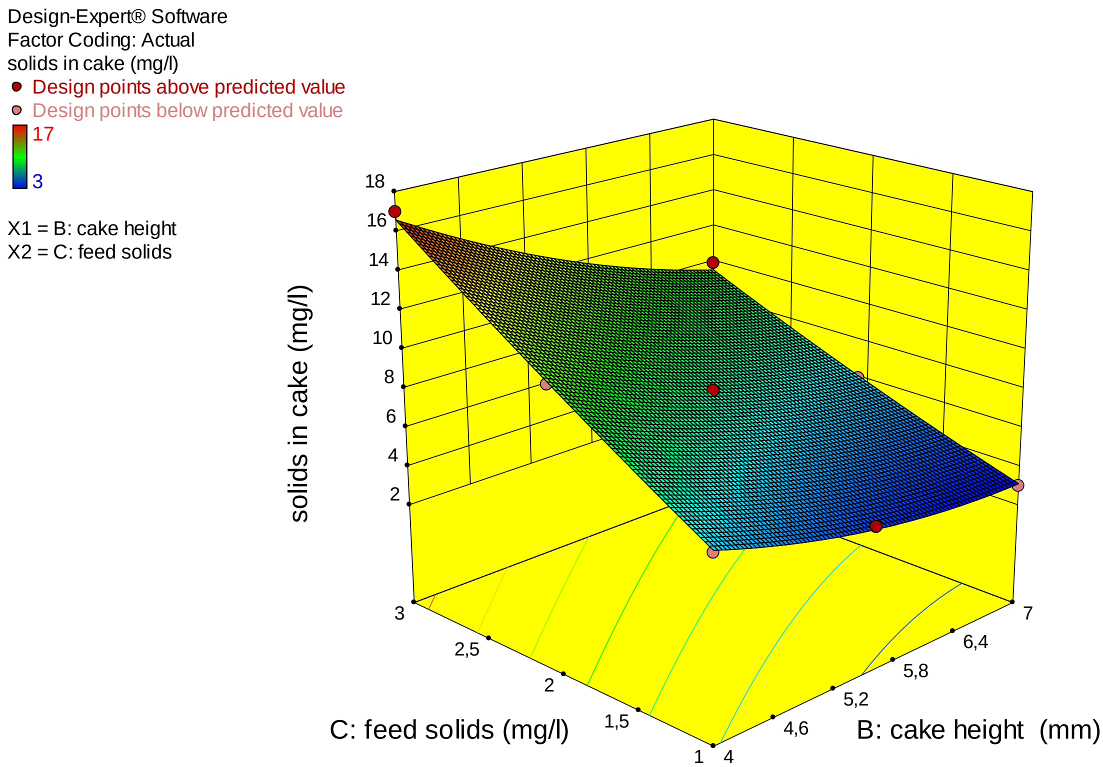
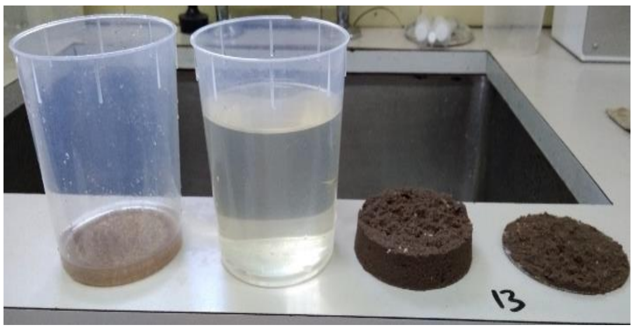


Figure 4.11: 3D surface plot showing the effect of cake height and feed solids on the solids in cake concentration

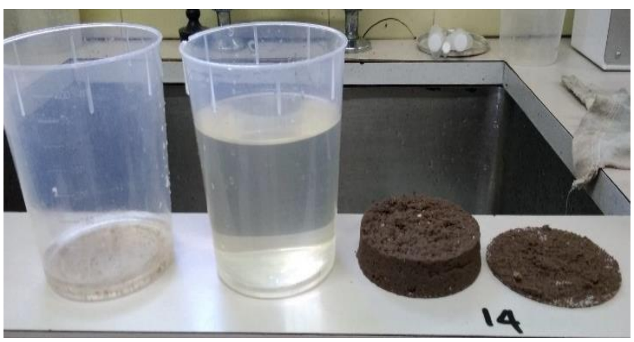
4.6.3 Visual observation of cake height and filtrate quality

The image's below is the result of the bench press experiment, gravity filtration the second beaker, compression filtration after 2 bar pressure was applied, first beaker. Lastly, the cakes produced for each WWTP.

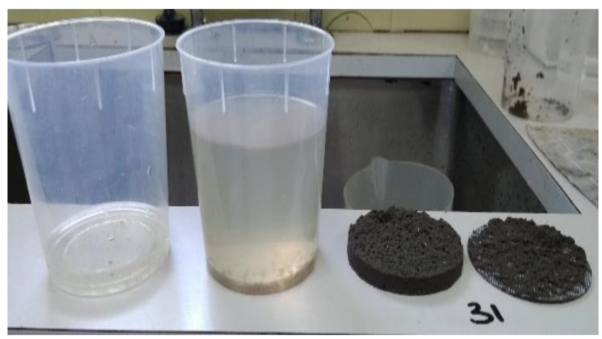


(1)

(2)



(3)



(4)

Photograph 4.2: The end results for the bench press experiment:

(1) WWTP A, (2) WWTP B, (3) WWTP C and (4) WWTP D

A preliminary test is necessary to adjust sludge mass to obtain the desired cake height of 3 mm – 4 mm, as discussed in chapter 3. Another possibility is to impose a given dry solids content before commencing the experiment runs. However, this may lead to different cake heights. The procedure that was used for this experiment was to allow the WAS to settle to produce a thicker sludge to produce a visible cake height as seen in the images above. The calculation to obtain the cake height is presented in Equation 8 of Chapter 3.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

In this study, sludge dewaterability was investigated by a drainage control and a compression test. The aim was to identify which dewatering parameter affects the sludge dewatering operation by investigating the sludge characteristics of four MWWTWs with two different polymers at various concentrations. During the flocculation make-up, various polymer dilution water types were used.

The most influencing sludge characteristics were identified as the volatile suspended solids and the feed solids concentration. At the end of the bench press test, an inversely proportional relationship between the volatile suspended solids and the percent solids in the cake could be deduced. The waste activated sludge with a high volatile suspended solid would yield a low percentage solid in the sludge cake after compression is applied.

The feed solids found in waste activated sludge is also a vital sludge characteristic due to it being the initial step to check before conducting any experimental work. This parameter will direct the type of sludge that is being produced. Feed solids will also indicate how much polymer would be required during the flocculation stage of the experimental work. Hence, the importance of the feed solids concentration of the waste activated sludge at hand.

By changing the polymers used and by varying the concentrations, it was observed that a higher molecular weight polymer does not necessarily mean better sludge dewatering, in terms of filtrate clarity and sludge cake moisture content. For waste activated sludge with a low feed solid content using the lower molecular weight polymer should be adequate to produce a sludge cake moisture content between the ranges of 15 – 25 %.

There are other parameters to focus on other than changing the polymer type or concentration, such as the polymer dilution water. All four of the MWWTWs used for this study uses different polymer dilution water types, which are produced at the facilities. This research study has shown that MBR effluent provided the highest drainage volume in the shortest time during the drainage control test and used the least amount of polymer for sludge and polymer solution flocculation. However, since not all four MWWTWs has the MBR facilities, the characteristics of the treated effluents produced and used at the sludge dewatering facilities should be close to the MBRs treated effluent characteristics as far as possible.

Design Expert was used to checking the correlation of polymer dosage, cake height, and feed solids concentration to the cake solids concentration. By using this statistical procedure, it was found that the results followed a Box-Behnken Design (BBD), and a quadratic model was formed. The reason for selecting the BBD was due to this experiment having three factorial levels, minimum, optimum, and overdosing for polymer dosing. The BBD requires three levels for each factor to obtain a quadratic model for the data supplied via the experimental test. The selected factors (cake height, feed solids concentration, polymer dosage) and response (cake solids concentration) were found to be significant with an $R^2 = 0.9950$.

The measurement of sludge dewaterability can become extremely complicated if all factors are taken into consideration. This is due to waste activated sludge characteristics varying continuously; therefore, testing its dewaterability regularly is essential.

5.2 Recommendation

It would be more efficient to assess not only waste activated sludge but other sludge types as well, to compare results and to check the efficiency of the dewatering operations more broadly. Lab-scale instrumentation such as a TSS meter is important for the measurement of filtrate suspended solids after filtration.

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APPENDICES

APPENDIX A

A.1 Raw data (Waste Activated Sludge)

Table A.1: WAS Plant A data

PLANT A		
SLUDGE PARAMETERS	UNITS	
Settleable Solids	ml/l	653
Total Suspended Solids	mg/l	3903
Volatile Suspended Solids	mg/l	3230
SVI	ml/g	148
DSVI	ml/g	123
PH		7
RAS Suspended Solids	mg/l	6357

Table A.2: Was Plant B data

PLANT B		
SLUDGE PARAMETERS	UNITS	
Settleable Solids	ml/l	927
Total Suspended Solids	mg/l	9282
Volatile Suspended Solids	mg/l	7162
SVI	ml/g	104
DSVI	ml/g	78
PH		7
RAS Suspended Solids	mg/l	12644

Table A.1.3: WAS Plant C data

PLANT C		
SLUDGE PARAMETERS	UNITS	
Settleable Solids	ml/l	982
Total Suspended Solids	mg/l	8512
Volatile Suspended Solids	mg/l	7162
SVI	ml/g	117
DSVI	ml/g	107
PH		7
RAS Suspended Solids	mg/l	13094

Table A.1.4: WAS Plant D data

PLANT D		
SLUDGE PARAMETERS	UNITS	
Settleable Solids	ml/l	664
Total Suspended Solids	mg/l	7746
Volatile Suspended Solids	mg/l	7068
SVI	ml/g	103
DSVI	ml/g	70
PH		7
RAS Suspended Solids	mg/l	9565

A.2 Effluent information

Table A.2.1: MBR Plant B effluent data

MBR Plant B		
Total Suspended Solids	mg/l	6,0
COD	mg/l	34,8
Ammonia	mg N/l	0,9
Nitrate/Nitrite	mg N/l	9,1
Ortho-Phosphate	mg P/l	0,3
pH		7,4
Conductivity	mS/m	103,8
Chloride	mg/l	157,3
Alkalinity	mg CaCO3/l	185,8
E.Coli	per 100ml	34,9

Table A.2.2: MBR Plant C effluent data

MBR Plant C		
Total Suspended Solids	mg/l	5
COD	mg/l	38
Ammonia	mg N/l	7,0
Nitrate/Nitrite	mg N/l	26,2
Ortho-Phosphate	mg P/l	0,8
pH		7,0
Conductivity	mS/m	98
Chloride	mg/l	125
Alkalinity	mg CaCO3/l	93
E. Coli	per 100ml	26

Table A.2.3: Treated effluent before filtration data

Treated effluent after filtration		
Total Suspended Solids	mg/l	24
COD	mg/l	92
Ammonia	mg N/l	38,8
Nitrate + Nitrite	mg N/l	5,7
Ortho-Phosphate	mg P/l	5,6
pH		7,4
Conductivity	mS/m	154
Chloride	mg/l	233
Alkalinity	mg CaCO3/l	333
Turbidity	NTU	2,72
E. Coli	per 100ml	16

Table A.2.4: Treated effluent after filtration data

Treated effluent after filtration		
Total Suspended Solids	mg/l	10
COD	mg/l	87
Ammonia	mg N/l	37.8
Nitrate + Nitrite	mg N/l	2.4
Ortho-Phosphate	mg P/l	7.5
pH		7.5
Conductivity	mS/m	156
Chloride	mg/l	242
Alkalinity	mg CaCO3/l	328
E. Coli	per 100ml	10758

A.3 Gravity drainage test data and results

FIELD LABORATORY GRAVITY BELT PRODUCT EVALUATION										
X Municipality: Plant X Wastewater Treatment Works						**Contact name :**				
Plant Manager: xxxxxxxx						**Contact Numbers:**				
									Ref. :	
Nature of sludge: Digested Sludge			**Dewatering equipment :**			**Make-up unit: Powder**				
Type of sludge: 90% Domestic and 10%Industrial			Belt Press	4 Delkor Tech					Test date	2018/03/27
Incoming Solids:	1,41					Polymer conc. :	0,20%		Page n° :	1
	0,0141	Product Dosage Profile: FO 4490 - Using Potable Water for Poly make-up								
TEST N°	**1**	**2**	**3**	**4**	**5**					
Polymer reference	FO 4650	FO 4650	FO 4650	FO 4650	FO 4650					
Dissolution concentration (g/l)	2	2	2	2	2					
Dosage (ml)	3,5	4	4,5	5	5,5					
Dosage (kg/ Ton)	**1,24**	**1,42**	**1,60**	**1,77**	**1,95**					
Mixing (n)	6	6	6	6	6					
The aspect of the flocs	**Tiny - Small**	**Small**	**Medium**	**Large**	**Large**					
Volume after garvity drainage (ml)	**145,87**	**143,80**	**140,63**	**156,20**	**164,67**					
Volume after belt press (ml)	**100,3**	**89,7**	**99,4**	**76,8**	**77**					
Final Filtrate (gravity)	small fine particles	small fine particles	small fine particles	Clear	Clear					
General mark	,+	,++	,++++	,++++	,++++					
Comment:										
				S = Small	M = Medium		V = Very			
		NOTE :	- : poor	+ : weak	++ : good	+++ : very good ++++ : excellent				

Figure A.3.1: Polymer consumption spreadsheet

Table A.3.1: Gravity Drainage results for FLOPAM 4800 at C = 2 g/l

Poly type: Flopam 4800 C = 0,2%

Water type	TEB	MBR	TEA	Potable	TEB	MBR	TEA	Potable	TEB	MBR	TEA	Potable	TEB	MBR	TEA	Potable
Plant	A				B				C				D			
overlapping volume (ml)	132	110	122	134	118	118	98	126	130	112	118	130	38	28	14	32
	148	126	114	122	130	120	116	154	134	130	140	120	20	24	6	16
	118	112	120	132	110	78	130	112	120	142	130	146	30	18	10	
Average	133	116	119	129	119	105	115	131	128	128	129	132	29	23	10	24
Heighest drained volume in 10 secs(ml)	132	142	138	140	160	152	142	150	128	132	136	136	36	40	18	48
	146	132	140	130	142	146	134	144	138	138	140	128	48	46	26	32
	130	126	138	128	148	146	134	142	136	156	148	140	30	34	16	22
Average	136	133	139	133	150	148	137	145	134	142	141,3333	134,6667	38	40	20	34

Table A.3.2: Gravity Drainage results for FLOPAM 4800 at C = 3 g/l

Poly type: Flopam 4800 C = 0,3%

Water type	Wash	MBR	Re-Use	Potable	Wash	MBR	Re-Use	Potable	Wash	MBR	Re-Use	Potable	Wash	MBR	Re-Use	Potable
Plant	A				B				C				D			
overlapping volume (ml)	140	122	132	148	128	132	110	142	142	128	132	148	60	32	40	48
	156	138	124	136	140	134	128	170	146	146	154	138	56	32	34	56
	126	124	130	146	120	92	142	128	132	158	144	164	54	18	32	60
Average	141	128	129	143	129	119	127	147	140	144	143	150	57	27	35	55
Heighest drained volume in 10 secs(ml)	140	154	148	154	170	166	154	158	140	148	150	156	68	46	50	64
	154	144	150	144	152	160	146	160	150	154	154	148	52	38	46	70
	138	138	148	142	158	160	146	153	148	172	162	160	70	38	38	68
Average	144	145	149	147	160	162	149	157	146	158	155	155	63	41	45	67

Table A.3.3: Gravity Drainage results for FLOPAM 4560 at C = 2 g/l

Poly type: Flopam 4650 C = 0,2 %

Water type	TEB	MBR	TEA	Potable	TEB	MBR	TEA	Potable	TEB	MBR	TEA	Potable	TEB	MBR	TEA	Potable
Plant	A				B				C				D			
overlapping volume (ml)	110	130	130	132	128	98	118	120	128	134	136	126	10	8	16	18
	120	128	102	134	116	130		120	130	132	142	130	8	14	12	20
	110	142	102	136	128	114		130		142	122	140	4	18	10	16
Average	113	133	111	134	124	114	118	123	129	136	133	132	7	13	13	18
Heighest drained volume in 10 secs(ml)	162	158	146	142	132	132	128	134	142	154	140	146	18	20	26	20
	156	158	156	142	134	132		144	144	148	148	152	20	22	22	24
	158	146	156	148	128	136		132		148	156	140	24	18	28	18
Average	159	154	153	144	131	133	128	137	143	150	148	146	21	20	25	21

Table A.3.4: Gravity Drainage results for FLOPAM 4560 at C = 3 g/l

Poly type: Flopam 4650 C = 0,3%

Water type	TEB	MBR	TEA	Potable	TEB	MBR	TEA	Potable	TEB	MBR	TEA	Potable	TEB	MBR	TEA	Potable
Plant	A				B				C				D			
overlapping volume (ml)	121	120	126	133	123	108	108	123	129	123	127	128	30	48	46	40
	134	127	108	128	123	125	116	137	132	131	141	125	18	50	32	40
	114	127	111	134	119	96	130	121	120	142	126	143	28	36	36	40
Average	123	125	115	132	122	110	118	127	127	132	131	132	25	45	38	40
Heighest drained volume in 10 secs(ml)	147	150	142	141	146	142	135	142	135	143	138	141	40	44	38	60
	151	145	148	136	138	139	134	144	141	143	144	140	52	56	32	60
	144	136	147	138	138	141	134	137	136	152	152	140	38	42	36	56
Average	147	144	146	138	141	141	134	141	137	146	145	140	43	47	35	59

A.4 Belt Press Results

Table A.4.1: Plant A Belt press data

Plant A						
Solids in feed	**%**	1,87				
Poly dosage	**ml**	12	13	14	15	16
Poly consumption	**kg/DTS**	3,59	3,89	4,19	4,49	4,79
Gravity drainage	**ml**	296,90	291,90	294,00	296,90	308,00
Pressed drainage	**ml**	11,85	14,35	12,70	7,40	13,35
Start weight	**g**	0,53	0,54	0,57	0,51	0,55
Solids in cake	**%**	14,49	16,90	18,13	18,94	18,47
Drying time	**mins**	21,45	22,96	33,46	27,86	27,22
Cake height	**mm**	5	6	2	4	4

Table A.4.2 Plant B Belt press data

Plant B						
Solids in feed	**%**	2,02				
Poly dosage	**ml**	12	13	14	15	16
Poly consumption	**kg/DTS**	3,59	3,89	4,19	4,49	4,79
Gravity drainage	**ml**	301,90	311,05	298,60	298,90	311,65
Pressed drainage	**ml**	22,30	22,95	21,75	26,75	20,85
Start weight	**g**	0,54	0,56	0,54	0,51	0,54
Solids in cake	**%**	15,57	18,44	18,79	19,04	16,12
Drying time	**mins**	21,70	28,81	23,00	23,01	21,39
Cake height	**mm**	3	3	2	1	1

Table A.4.3 Plant C Belt press data

Plant C						
Solids in feed	**%**	2.13				
Poly dosage	**ml**	13	14	15	16	17
Poly consumption	**kg/DTS**	3,59	3,89	4,19	4,49	4,79
Gravity drainage	**ml**	272,85	286,30	285,25	271,15	570,20
Pressed drainage	**ml**	17,40	19,30	16,05	19,00	18,50
Start weight	**g**	0,52	0,54	0,55	0,54	0,57
Solids in cake	**%**	12,96	13,08	12,22	12,14	12,25
Drying time	**mins**	35,99	28,37	26,37	26,33	30,34
Cake height	**mm**	9	10	11	12	13

Table A.4.4 Plant D Belt press data

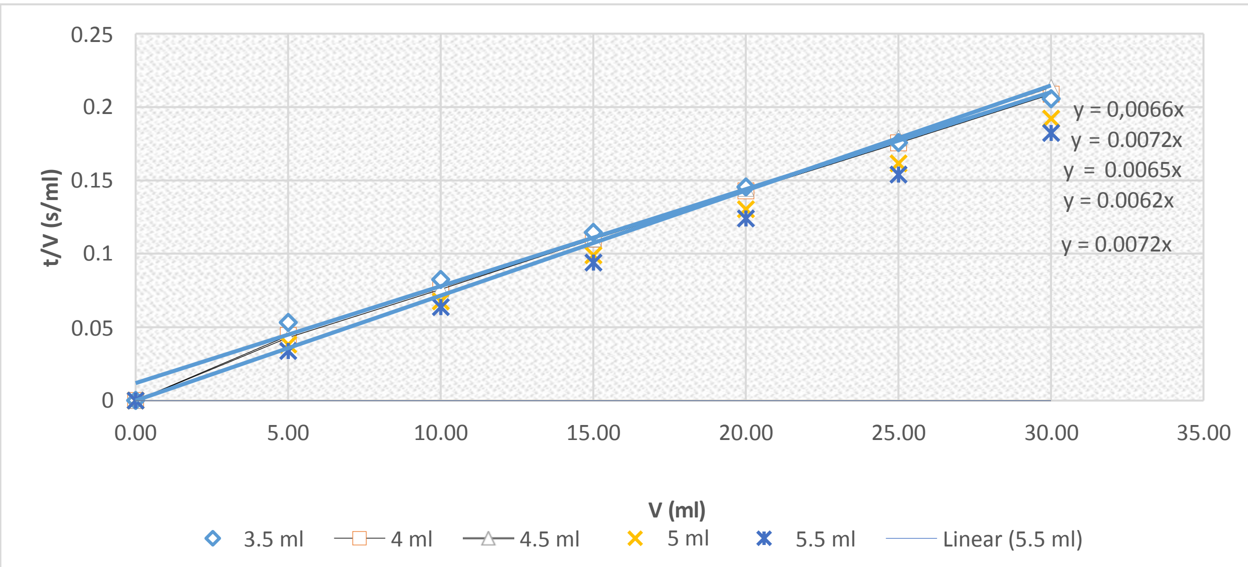
Plant D						
Solids in feed	**%**	2,18				
Poly dosage	**ml**	30	31	32	33	34
Poly consumption	**kg/DTS**	3,59	3,89	4,19	4,49	4,79
Gravity drainage	**ml**	286,40	278,90	285,15	301,10	305,15
Pressed drainage	**ml**	8,95	18,90	12,85	8,40	6,80
Start weight	**g**	0,58	0,59	0,55	0,52	0,57
Solids in cake	**%**	13,47	15,57	15,06	15,93	16,57
Drying time	**mins**	29,79	21,53	25,77	24,60	26,26
Cake height	**mm**	7	8	6	6	7

APPENDIX B

Calculation of the SRF

The SRF was determined after a linear plot of t/V vs. V was done. The displayed results for the SRF obtained in chapter 4 was for plant A WAS, treated effluent before filtration for both polymers at 0.2% concentration.

The b (constant) value was determined from the slope of the linear plot (t/V vs. V).



The SRF was calculated using the equation below

$$SRF = \frac{2\Delta P A^2 b}{\mu\omega}$$

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Table B.1: Parameters used to calculate SRF

Calculating SRF			
Assumptions			
P	1038.47	g/cm^2	Liquid pressure
µ	4400	g/cm sec	the viscosity of polymer solution (Knocke, 1992)
α, SRF		(s^2/g)	uniform resistance across the cake
Parameters			
A	63,62	cm^2	
D	9	cm	
π	3,141		
Ci	98,13	g/ml	
Cf	84,84	g/ml	
C	0,021	g/ml	

Obtaining the pressure exerted by the liquid was obtained using the equation below:

$$\mathbf{P = h\rho g}$$

- The height of the sludge and polymer mixture was 5 cm at the start of the drainage control test.
- g = gravitational acceleration is 10 m/s^2
- ρ = density of waste activated sludge was found to be 1.038 g/cm^3

Table B.2: Results obtained for the SRF

Polymer dosage (ml)	3,5	4	4,5	5	5,5
b values	0,0072	0,0071	0,0071	0,0065	0,0062
SRF (sec2/g)	6,45E+05	6,36E+05	6,36E+05	5,82E+05	5,55E+05

According to previous work (Valexaire & Olivier, 2007), the SRF values obtained for this study were low which implies that this sludge type should be easy to dewater.

Sample calculation for obtaining the SRF value:

Obtaining the SFR:

- The change in pressure for filtration is the liquid pressure exerted onto the filter medium, therefore:

  $$\mathbf{P = h\rho g}$$

  $$\mathbf{\Delta P = 1038.48\ \frac{g}{cm^2}}$$

- The value for b was obtained from the slope of the graph of volume vs. time/volume

- $\boldsymbol{A = \pi r^2 = 63.62cm^2}$

- $\boldsymbol{\omega = C = \frac{1}{\frac{C_1}{100-C_1} \times \frac{C_f}{100-C_f}} = 0.021\ \frac{g}{ml}}$

- $\boldsymbol{SRF = \frac{2\Delta PA^2b}{\mu\omega} = \frac{2\times 1038.48\times 63.62^2\times 0.0072}{4400\times 0.021} = 6.45x10^5\,\frac{s^2}{g}}$

APPENDIX C

Process flow diagram of WWTP

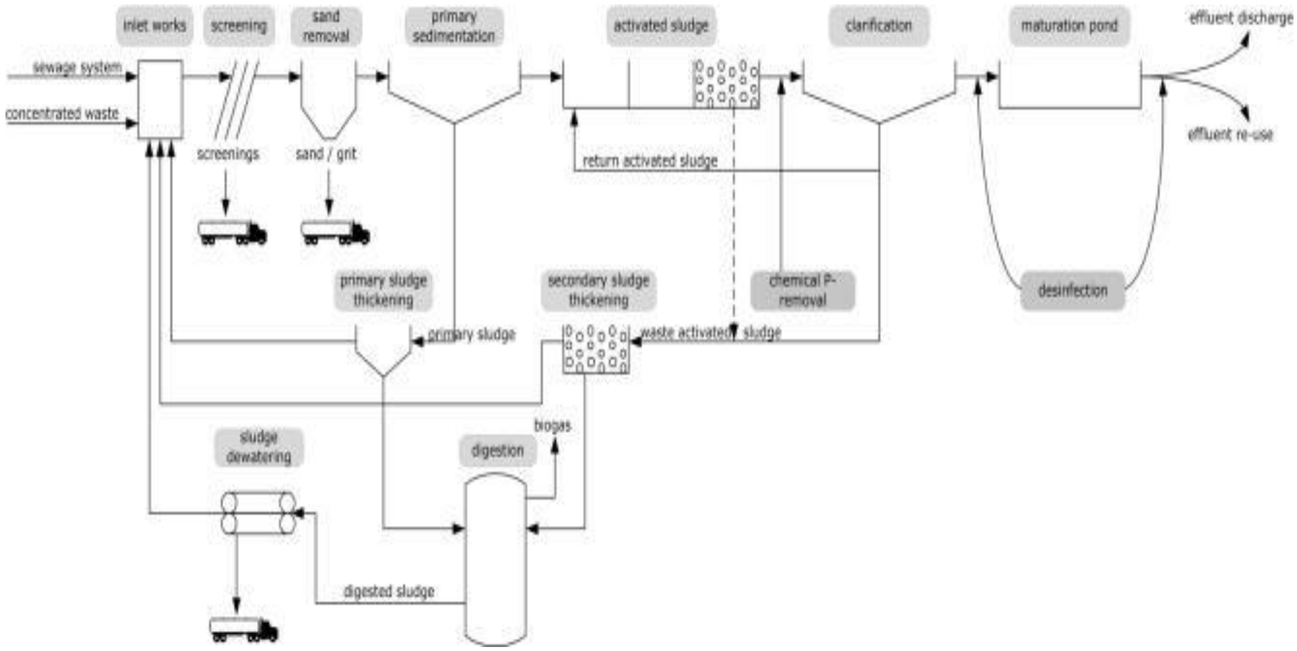

Figure C.1: Process Flow Diagram for the Wastewater Treatment plant

APPENDIX D

Development of the sludge dewatering model in terms of solids in cake omitted results

The parameters/factors omitted from design expert was the interaction polymer dosage and cake height. Based on the following graphs, populated with Design expert, the factors had no significant contribution to obtaining a statiscal relationship between them and the feed solids concentration and was therefore omitted from the results and discussion for this research.

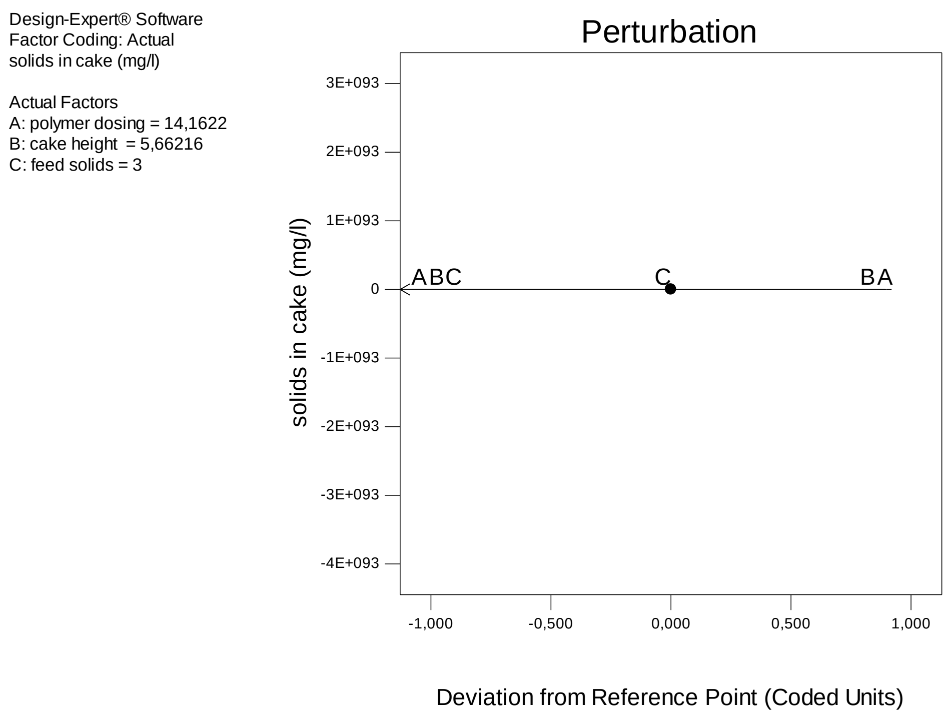

Figure D.1: Pertubation plot for feed solids concentration, cake height and polymer dosing

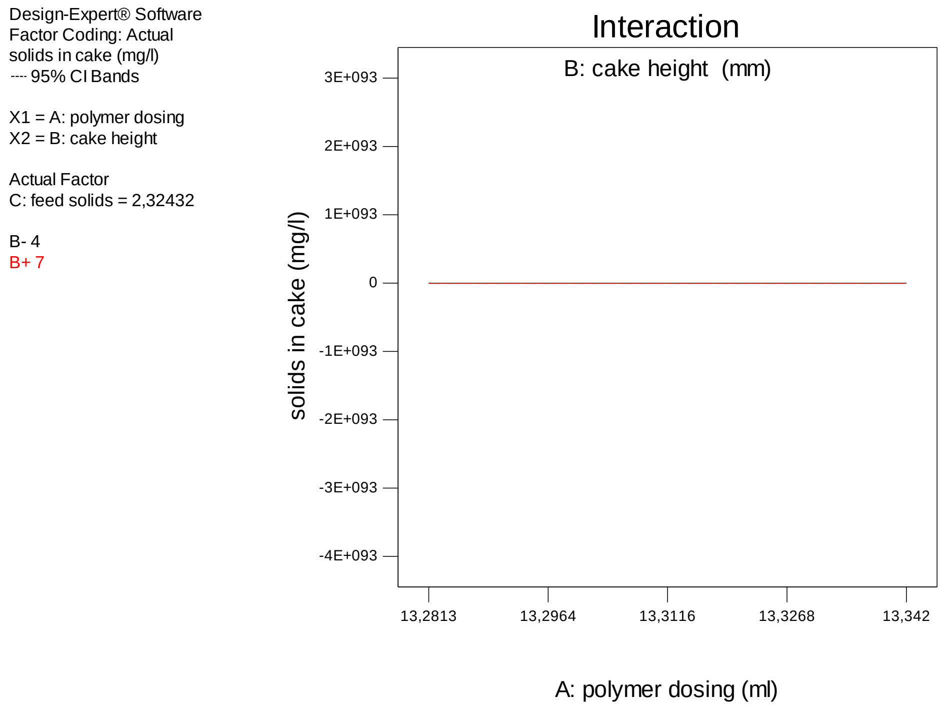

Figure D.2: Interaction plot for the effect of cake height and polymer dosing on solids in cake concentration

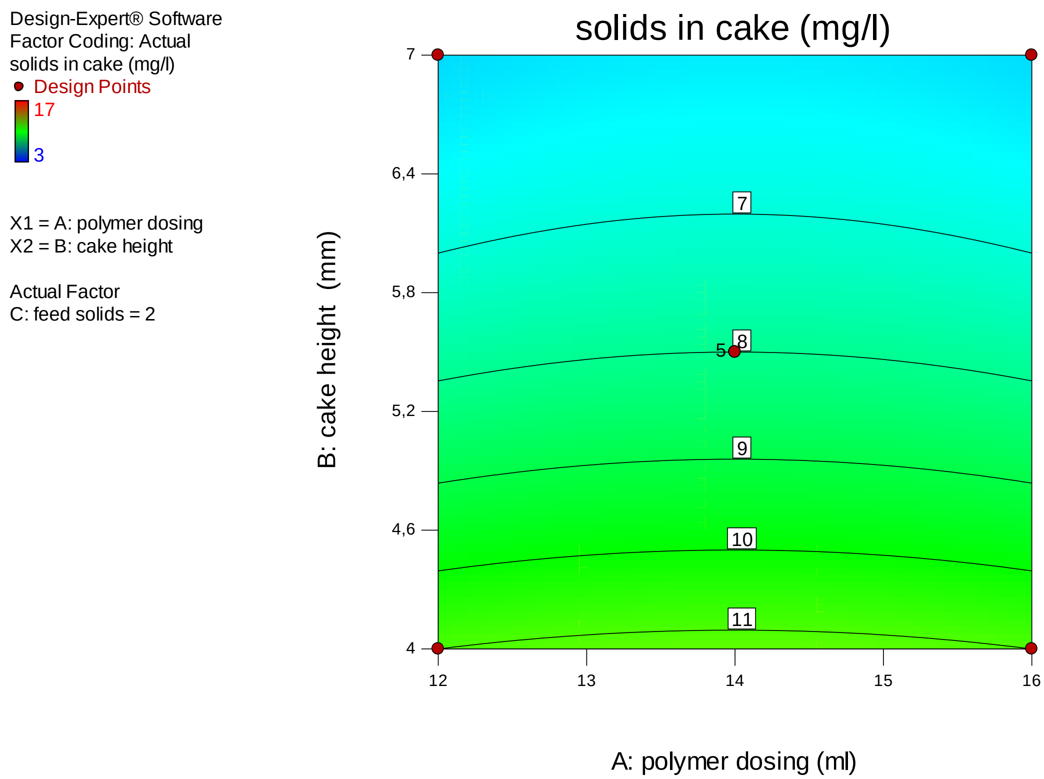

Figure D.3: 2D contour plot for the interaction of polymer dosing and cake height on solids in cake concentration

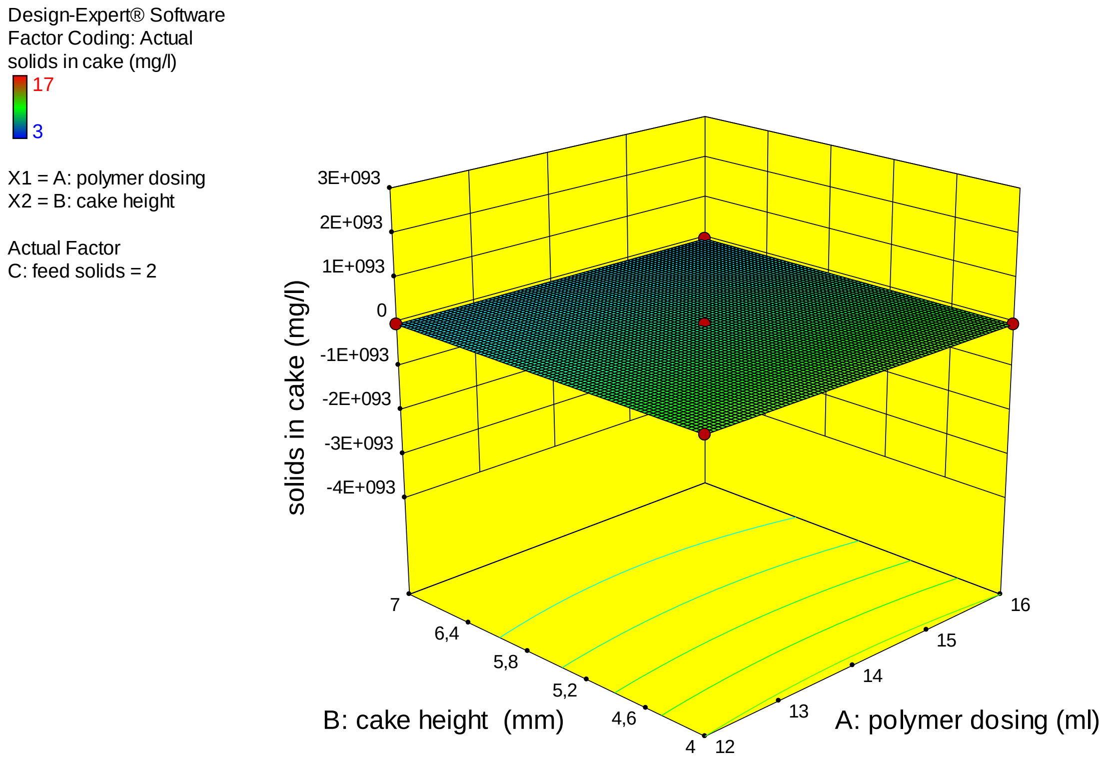

Figure D.4: 3D surface plot for the interaction of cake height and polymer dosing on solids in cake concentration