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INSTITUTE FOR TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS

OPTIMIZATION OF SLUDGE DEWATERING PROCESS AT BENSBERG MUNICIPAL WASTEWATER TREATMENT PLANT

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ABSTRACT

The main purpose of this research was to improve the sludge dewatering process at Beningsfeld municipal wastewater treatment plant in the municipality of Bergisch Gladbach, Germany. The purpose of improving the dewatering process is to achieve a better dried solids (DS) content. Several trials were carried to accomplish this objective, both at small and large scale. NALCO polyacrylamide based polymer was tested and the dosage was optimized in small scale trials; in the range of 7 to 8 mL polymer per 100 ml of digested sludge (7-8% V/V) the best CST values were obtained (8.96 and 9.94 seconds respectively), however when this range of dosage was tested in a trial at large-scale, there were no DS improvements detected. The Kemicond process (treatment with sulphuric acid and hydrogen peroxide) was also tested. The best results for 500 ml samples were obtained when the sludge's pH was decreased to 6 with H_2SO_4, followed by a treatment with 1 ml of H_2O_2, which proved to have good dewaterability results. Nevertheless, since it is a very aggressive treatment it requires special machinery and it could be environmentally harmful in the long run. In general, the dried cake total solids could not be improved; however, other parameters were found to be of importance on the mechanical dewatering process, such as: time of press filling, compression time, age and type of filter membrane, the quality of sludge entering the press and the polymer-sludge mixing.

RESUMEN

El objetivo principal de este trabajo de investigación fue mejorar el proceso de deshidratado de lodos para la planta de tratamiento de aguas residuales municipales Beningsfeld, localizada en la municipalidad de Bergisch Gladbach, Alemania. Se quiere optimizer el proceso de deshidratado con el propósito de aumentar la concentración de sólidos en el lodo. Para este fin, se realizaron varias pruebas a nivel laboratorio y a escala industrial. Se probó un polímero basado en poliacrilamida (NALCO) y se optimizó la dosis a pequeña escala. Se obtuvieron los mejores valores de CST en el rango de 7 a 8 mL de polímero por cada 100 mL de lodo digerido (7-8% V/V), obteniendo valores de CST de 8.96 y 9.94 segundos respectivamente; sin embargo, cuando este rango fue probado en escala real, no se observaron mejorías. Adicionalmente, se probó el proceso Kemicond (tratamiento con ácido sulfúrico y peroxido de hidrógeno) para el acondicionamiento del lodo. Para muestras de lodo digerido de 500 mL, los mejores resultados se obtuvieron cuando el pH se disminuyó hasta 6 mediante H_2SO_4 y fue tratado posteriormente con 1 ml de H_2O_2; sin embargo, es un tratamiento muy agresivo y require de maquinaria especial y a la larga se podría generar mayor contaminación por lo que no es factible su aplicación a gran escala. En general los resultados de sólidos totales de la torta filtrada no fueron mejoraros; sin embargo, se encontraron otros parámetros de importancia para la deshidratación mecánica, los cuales fueron: tiempo de llenado de la prensa, tiempo de compresión, edad y tipo de membranas, así como la calidad del lodo de entrada.

ZUSAMMENFASSUNG

Das Hauptziel der vorliegenden Forschungsarbeit war es, den Schlammentwässerungsprozess in der kommunalen Kläranlage der Stadt Bergisch Gladbach zu verbessern, um eine höhere Feststoffkonzentration zu erreichen. Dazu wurden verschiedene Versuche sowohl im Labor als auch in der Kläranlage durchgeführt. Hierbei wurde ein auf Polyacrylamid basierendes Polymer (NALCO) getestet, dessen Dosierung im Labor optimiert wurde. Die besten CST-Werte (8,965 s bzw. 9,94 s) wurden im Bereich von 7 bis 8 ml Polymer je 100 ml Faulschlamm (1 % V/V) erzielt. Bei der Durchführung der Versuche im Klärwerk selbst wurde jedoch keine Verbesserung der Trockensubstanzwerte festgestellt. Das Kemicond-Verfahren (Behandlung mit Schwefelsäure sowie Wasserstoffperoxid) wurde zur Schlammkonditionierung ebenfalls getestet. Die besten Ergebnisse wurden bei den untersuchten Faulschlammproben von 500 ml bei einer Absenkung des pH-Wertes auf 6 durch die Zugabe von H_2SO_4 sowie einer nachfolgenden Behandlung mit 1 ml H_2O_2 erzielt. Diese Behandlung ist jedoch sehr aggressiv und erfordert spezielle Maschinen. Auf lange Sicht kann sie sich ökologisch schädlich auswirken. Im Allgemeinen konnte der Feststoffgehalt des Filterkuchens nicht verbessert werden. Jedoch, weitere wichtige Kenngrößen, die einen Einfluss auf die mechanische Schlammentwässerung hatten, waren die Dauer des Schlammzulaufs in die Presse, die Dauer der Pressung, Alter und Typ der Filtertücher, die Qualität der zugeführten Schlämme sowie die Vermischung der Polymere mit dem Schlamm.

CHAPTER 1. INTRODUCTION

Sludge is an unavoidable waste product originated from the treatment of municipal wastewater, the sludge contains all of the harmful substances which were removed from the waste water (Metcalf and Eddy, 2003), including organic matter, pathogens and chemical contaminants, and needs to be processed to reduce its environmental and health impacts for its later reuse or disposal.

The treatment and disposal of this sludge, accounts for a major portion of costs of wastewater treatment facilities. Additionally, new standards have been established by the environmental institutions and more restrictive regulations are executed every year for this matter. (Mesdaghinia, 2004).

In 2003 approximately two million tonnes of sewage sludge were produced in Germany. (UN-Habitat, 2006). , Table 1 shows general data about Germany and sludge production per capita per year.

Table 1. General data about Germany, and sludge destination and production.

Area	**Population**		**Sludge Destination**			**Relative Sludge Production**
km2	Million	Density	Total	Reuse	%	kg/person/year
131.95	10.5	80	99	7	7	9

Source: Table 1-1: Area, population and sewage sludge production of EU member states in the year 2005. (MAGOAROU 2000), page 9. Retrieved from: http://ec.europa.eu/environment/waste/sludge/pdf/organics_in_sludge.pdf

This table shows that only a small part of the sludge is designated for reuse for land application, and the rest most likely goes to incineration, which is a very costly route. The rising costs for sludge disposal for German facilities make indispensable to optimize processes focused on the reduction of volume and mass, such as the thickening and the mechanical dewatering process. The main goal of improving the dewatering process is to reduce the volume of sludge to be disposed; On one hand this reduction will be directly reflected on the cutback of sludge disposal costs for the treatment facility, and on the other hand, it will reduce its environmental impact as there would be less sludge to be disposed off and energy used for incineration would also be saved.

Sorensen (1996) (retrieved from Dominiak, 2010), reported that 30–50% of the annual operating costs of waste water treatment facilities are related to sludge dewatering alone. This could be mainly due to the mechanical complexity of the process and to the use of chemical aids. However, the use of a chemical conditioning step is absolutely necessary for the mechanical dewatering by using filter press, since otherwise very poor yields would be obtained. With the use of conditioners, greater yields and flexibility can be obtained and it can also reduce water content from 90-99 % to 65-85% (Dominiak, 2010).

This research focused on the optimization of chemical conditioning of sludge in order to obtain better dewatering yields and to use the minimum amount of dewatering additives. Another purpose was to search for the main parameters that affect the mechanical dewatering process and give a review of the sludge dewatering conditioners and new trends on natural flocculating aids for the production of less harmful sludge.

CHAPTER 2. BENINGSFELD WASTEWATER TREATMENT PLANT

2.1. General Description

This research was carried in Beningsfeld Waste Water Treatment Plant (WWTP) (Figure 1), a municipal wastewater treatment plant located in the municipality of Bergisch Gladbach, Germany.

When the Bergisch Gladbach sewage treatment plant was built between 1974 and 1977, it was conceived as a one-stage mechanical-biological sewage treatment plant with a capacity of 130,000 inhabitants. Between 1989 and 1991, the WWTP was expanded and adjusted to the new, more rigorous requirements for nitrogen and phosphorous removal. Another reason for the plant's expansion was a projection of 200,000 inhabitants for the year 2000. The treatment of storm water and sludge handling was also taken into account. Table 2 shows an overview of the design parameters of the plant.

Table 2. Design parameters for Beningsfeld Wastewater Treatment Plant

Parameter	Dimension	Value
Inhabitants	Inhabitants	166,000
BOD_5/Inhabitant	$kgBOD_5$/inh/d	72
Total Load	m^3/d	11,950
Daily dry weather flow	m^3/d	31,369
Middle dry weather flow per hour	m^3/h	1,306
Maximum dry weather flow per hour	m^3/h	2,112
Minimum flow per hour	m^3/h	735
Maximum storm flow per hour	m^3/h	4,212

Retrieved from: Radtke, 2005 pg.2

Inflow to the wastewater treatment plant (WWTP).

The inflow received by the WWTP is composed of two different sub-streams. The inflow from Ortsteilen from the municipal area of Bergisch Gladbach which comes from a separated system, and the inflow from Gebiet Bensberg which comes from a mixed and separated system. The two sub-streams are later combined and equalized.

The catchment areas for Beningsfeld Wastewater Treatment plant are shown on

Table 3, the m^3 represent the volume of mixed inflow that is collected per year.

Table 3. Catchment Areas in Development for Beningsfeld Wastewater Treatment Plant (2000).

Catchment area	m^3
Bergisch Gladbach	50,542
Bensberg	38,914
Plackenbruch	86
Unterboschbach	156
Leverkusen	6,500
Köln Brück	300
Odenthal	2,000
Total	98,498

Retrieved from: Radtke, 2005 pg.3

The plant's current capacity is of 200,000 inhabitants and it operates at 70 per cent of its full capacity. Beningsfeld wastewater treatment plant can treat an approximate flow of 4,212 m^3 per hour. Additionally, the facility produces 7,000 tones of sludge per year.

Figure 1. Beningsfeld Waste Water Treatment Plant

2.2. Wastewater Treatment Process at Beningsfeld WWTP.

2.2.1.Pre-Treatment

Screening

The first mechanical process for the treatment is screening. The main purpose of this operation is to remove coarse material that could damage equipment or that could generate an efficiency loss in the overall treatment process. Also fine screens are sometimes implemented as pretreatment to protect equipment and to eliminate harmful material that would make impossible the reuse of bio-solids.

The equipment used consists on mechanically raked bar screens. The raking system removes coarse material, large solids such as plastic components and fibrous materials from the wastewater stream. This is necessary to avoid a clogging of the pipes and counteract wearing and destruction of the pumps. The raking system consists of two parallel step screens with 6 mm bar spacing.

If there are any incidents, the entire system can be bypassed by an emergency diversion, and can be fed untreated to the next part of the plant. The retained coarse material is transported to a wash press in which the easily degradable substances are washed out. The remaining waste is drained, pressed and then stored in a container tank until it is transported to the landfill site.

The drained water is returned to the inflow of the plant. To avoid unpleasant odors, the screening system is enclosed. Air is continuously extracted and fed to the bio-filter for purification.

Sand Trap

The sand trap serves for the removal of sands and other minerals for there is a risk that sediments will disturb the biology in the tanks. Furthermore, it could cause damage to pumping stations and lead to material wear. A longitudinal sand trap is used at Bergisch Gladbach. It consists of three channels with a length of 25 m and a width of 1.4 m. It also provides aeration through a rolling cylinder and has a flow rate of 0.3 m / s, so that the particles can settle and are not washed away with the outflow.

The sand that settled in the lower part is deposited in the collection channels and removed by using suction pumps and fed to a grit classifier. There, the sand is washed and conveyed into a container. The washing water used is returned to the inflow previous to the sand trap.

2.2.2.Primary Treatment

Primary sedimentation

Water from the sand grit flows into the pre-sedimentation tank. Here, the raw sludge is separated from water through settling. Settling is the separation of suspended particles that are heavier than water. The sedimentation of particles are based on the gravity force from the differences in density between particles and the fluid. (Bengt, 1998, pg. 1)

A successful sedimentation is very important for the overall efficiency of the water treatment plant. The settling process serves to remove all of the solids from suspension and to concentrate them for its further removal.

The infrastructure for this process consists on three rectangular tanks with a volume of 1,500 m^3 each. In tanks I and II, the sludge removal is carried by clearing scrapers, whereas in tank III the sludge is removed by a suction lifter. The floating sludge is removed by superficial clearing scrapers. The settled sludge is sent as excess sludge to the sludge treatment.

The removal efficiency of primary sedimentation is from 50 to 70 percent of suspended solids and from 25 to 40 percent of BOD.

2.2.3. Secondary Treatment

Activated Sludge Process

The biological treatment begins with the activated sludge process were compressed air is supplied to the system in order to enhance the microbiological decomposition of the organic matter. The activated sludge process consists basically on the aeration and mixing of wastewater with a group of selected microorganisms, usually in an aeration basin in which microorganisms metabolize the suspended organic matter. Part of the organic matter is incorporated to the system's biomass and another part is oxidized to CO_2 and water to derive energy. This new biomass is removed by flocculation and settling. Part of this settled biomass is returned to the aeration tank and the remaining is sent to the waste sludge.

The activated sludge tank at Beningsfeld WWTP is a rectangular basin that consists in two rows. Each row consists of four smaller square zones with a volume of 1025 m^3

each. The four smaller zones are followed by a large rectangular area, which has a volume of 5900 m^3. Both the aerobic and anaerobic basins are equipped with agitation to prevent the activated sludge from settling down.

After the biological process, the water is pumped into three intermediate settling tanks, were the biomass produced during the activated sludge process is settled down. Part of the biomass is recovered, and pumped back to the process through an elliptical pump to keep a continuous biomass concentration in the tank necessary for the degradation process, another part is sent to the anaerobic tank, which is used to optimize the biological phosphorous elimination.

Within the first 15 to 45 minutes, sludge adsorbs suspended solids and colloids. The biological oxidation comes about. The organisms in the activated sludge degrade the organic nitrogen compounds and destroy carbohydrates. The process begins rapidly at the beginning and then slows down within the next 2 or 5 hours. Then it continues to a constant speed during several hours. Generally the aeration lasts from 6 to 8 hours.

Nitrification and Denitrification

Denitrification takes place in the anoxic zone, which is held on basins 3 through 8, (Figure 2) in this zone only chemically bound oxygen is available. Nitrate (NO_3) is degraded to molecular nitrogen (N_2) by heterotrophic facultative bacteria. Also, organic carbon compounds are used as electron donors. The retention time in each basin is approximately 1.5 to 3 hours.

Nitrification takes place in the aerobic zone, Ammonium (NH_4) is converted into nitrite (NO_2) and later on to nitrate (NO_3), this is achieved by nitrificating bacteria which degrade inorganic substances under aerobic conditions. In the first step, the oxidation from ammonium (NH_4) to nitrite (NO_2), is carried out by *Nitrosomonas*. In the second step nitrite (NO_2) is oxidated to nitrate (NO_3) by *Nitrobacter*. Oxygen is used as electron acceptor and carbon dioxide as the main carbon source (Rittman, 2003).

Nitrification is operated in tanks 9 and 10 (Figure 2) with a volume of 5,900 m^3 each, and are aerated by diffusers. At the end of the nitrification tank, sludge is recirculated and fed into the denitrification zone.

Phosphorous removal

The limits of phosphorous discharge are between 0.10 and 2.0 mg/L. All methods for biological phosphorus removal are subject to fluctuations with regard to achieving low phosphorous concentrations. Therefore, it should also be combined with chemical precipitation to achieve the required quality. Chemical treatment using alum and alum salts are commonly used for phosphorous removal.

The chemical phosphate elimination is carried out in Basin 1 and 2. (

Figure 2). Through a simultaneous precipitation. Kronofloc is used as a precipitating agent; it comprises Iron II (Fe 2+), which is oxidized to Iron III (Fe 3+).

The stoichiometric equation of the precipitation reaction is shown in Equation 1. (Rybicki, 1997, pg.16).

$$Fe^{3+} + PO_4^{3-} \longrightarrow FePO_4$$

Equation 1

Secondary sedimentation

After treatment in the activation tanks, the waste water flows to the secondary settling process. This consists of two circular tanks with a volume of 3250 m^3 each and two rectangular tanks with a volume of 3100 m^3 each. The outflow from tank 9 flows into the two circular tanks, while that from tank 10 flows into the two rectangular basins (Figure 2). The average retention time spent at the circular tanks is approximately 6.2 hours and for the rectangular basin is 5.9 hours.

Secondary sludge settles after only 1.5 hours; it is removed by sludge scrapers (in the circular tank) or by suction scrapers (in the rectangular basin), and then part of the secondary sludge is recirculated to basins 1 and 2 into the activated sludge process.

Excess sludge is removed from the system by two submersible pumps and fed to the sludge treatment.

The treated waste water travels into a collection channel and is fed to the filtration area of the system described on the next subchapter.

2.2.4. Tertiary Treatment

Filtration

This is the last step in the treatment process; its main purpose is to remove suspended solids. The filtration system is designed as a backward-flow filtration and was put into operation in 1992. Filtration in Beningsfeld consists of eight rectangular tanks, with a length of 8.50 m and a width of 4.50 m.

The system has undergone through some renovations. Currently, it is made up of three layers, the first one is a support layer, followed by a quartz gravel layer (grain size from 0.71 to 1.25 cm) with a depthh of 0.6 m and the top layer is made out of anthracite (grain size 1.4 to 2.5 cm) with a depthh of 1.2 meters. Prior flocculation is required.

2.2.5. Effluent's quality

The final effluent at Bensberg WWTP has a phosphorous concentration of less than 1 mg/l and a total nitrogen concentration of less than 12 mg / l. These values are similar throughout the year.

The water obtained, has a quality such, that it can be poured directly into the river or other superficial water bodies without causing a negative impact in the aquatic life.

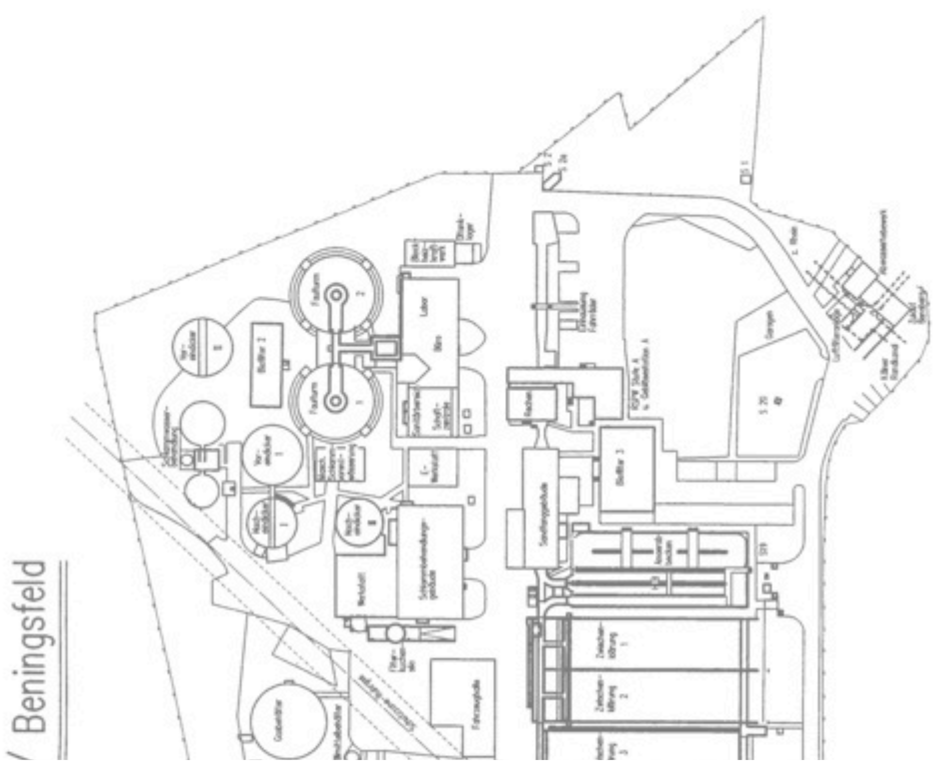

Figure 2. Bensberg wastewater treatment plant.

CHAPTER 3. SEWAGE SLUDGE

3.1. Definition

Sewage sludge means "any solid, semi-solid, or liquid residue removed during the treatment of municipal waste water or domestic sewage. Sewage sludge includes solids removed during primary, secondary or advanced; however it does not include grit, screenings, or ash generated during the incineration of sewage sludge." EPA, 2009. Sewage sludge typically contain from 0.25 to 12 percent solids by weight. (Metcalf and Eddy, 2003 pg.1449).

3.2. Types of sludge

Sewage sludge can be classified in four wide groups according to the operations and processes used.

Primary sludge consists mainly of organic solids, grit, and inorganic fines and is the sludge that normally comes from primary settling tanks.

Secondary sludge is biological sludge produced by treatment processes such as activated sludge, trickling filters, and rotating biological contactors.

Tertiary sludges or chemical sludges result from the addition of chemicals, such as coagulants and flocculats used to improve suspended solids removal or to precipitate phosphorus.

Treated sludge is the sludge which has undergone one of the treatment processes to significantly reduce its biodegradability and its potential to cause nuisance odors, as well as to prevent health and environmental hazards when it is used on land.

All of these sludges have low solids content (1-6 per cent) and thus large volumes of sludge must be handled to dispose a relatively small mass of solids. (AWWA, 1989). Table 4 shows the main sources of sludge from the different treatment operations and the dried solids content per volume.

Table 4. Amount of dried solids produced from different wastewater treatment processes.

Treatment process		Dried solids kg/10^3 m^3
Primary sedimentation		110-170
Activated sludge		70-100
Filtration		12-24
Chemical treatment for phosphorous removal	350-500mg/L lime	240-400
	800-1600 mg/L lime	600-1300

Suspended growth denitrification	12-30

Adapted from Table 14-7 Metcalf & Eddy, 2003, pg.1456.

According to Table 4. The main source of sludge comes from the chemical treatment, probably due to the amount of additives that need to be added, for instance lime, is generously added to regulate pH.

3.3. Sludge Quality

Sludge quality is based on its biological, chemical and physical properties. Also, sludge quality depends on the composition of the wastewater from which it is derived and the extent of processing that it receives during treatment. Biological properties include the microbiological stability of the organic matter in the sludge. Chemical properties include content of potentially toxic elements such as PTE's, heavy metals and organic contaminants. Physical properties are associated with the extent of thickening, dewatering or drying and aesthetic factors related with the removal of undesired material by effective treatment (CEN, 2002).

Calorific value may also be a quality criterion if the sludge is to be incinerated. The biological and physical qualities of sludge can be modified by treatment processes, which are necessary to meet reuse and disposal requirements. The sludge can have variations on its physical, chemical and biological properties due to its origin and to seasonal differences (CEN, 2002).

3.4. Types of water in the sludge

A very important parameter affecting the dewaterability of sludges is the state of the water in the sludge particles.

Sewage sludges have different textures and specific water binding capacities. This explains the significant differences in thickening and dewatering performances. The energy that must be provided to separate the solids from water in the sludge depends on its water binding capacity. Thermal treatment is sometimes applied since cell water, adhesive water, capillary and chemically bound water can only be thermally removed.

In general, for wastewater sludges, water is classified into two categories: free water and bound water.

Free water, represents the largest part of the sludge. This water can be eliminated by simple thickening or by the application of weak mechanical strains. (Smollen 1986; 1988 Retrieved from Collin, 1995, pg.2000)

Bound water, represents a very small proportion of the total water contained in the sludge but is generally greater in terms of mass than the solid phase. (Collin, 1995, pg.2000).

According to Roll and Halde (1979) there are three types of bound water:

(I) Chemically bound water, which is fixed to solids by strong chemical bindings, and can be eliminated by thermal drying at temperatures above 105°C.
(2) Physically bound water, which can be eliminated by thermal drying, and is fixed to the solid particles by adsorption or absorption.
(3) Mechanically bound water, which is found in both micro and macrocapillaries of capillary porous bodies. It can be fixed in the pores after the crystallization (Pyper, 1985) or the agglomeration of particles (Retreived from Collin 1995, pg. 2000).

3.5. Sludge Treatment

One of the two main objectives in treatment of sludge is to concentrate the solids by removing as much water as possible. Processes used with this purpose are thickening, sludge conditioning, dewatering and heat drying, among others. The other objective is to reduce the content of pathogens and of putrescible organic matter. Stabilization processes used for this purpose include aerobic and anaerobic digestion, and lime addition. There exist different possible flow paths that can be taken in the solids handling process. Different facilities may choose some of the processes to concentrate and stabilize solids while others may incorporate all of them.

Thickening. Is a procedure used to increase the solids content of sludge by removing a portion of the liquid phase. The volume reduction obtained by sludge concentration is beneficial to subsequent processes for the capacity of tanks required, quantity of chemicals required, and amount of heat required, it minimizes the unit load on downstream processes such as digestion and dewatering. (Metcalf and Eddy, 2003, pg.1488). The sludge concentration that can be achieved through this process is from 2 to 6 % of solids. Treatment plants commonly use thickening devices to increase the solids concentration. The most commonly used thickening processes is gravity thickening, although dissolved air flotation, gravity belt thickening, rotary drum thickening, and centrifuge thickening are also common.

Stabilization. Solids need to be stabilized by aerobic, anaerobic or lime stabilization to reduce pathogens, eliminate offensive odors, and inhibit or eliminate putrefaction (Metcalf and Eddy, 2003). Anaerobic digestion typically achieves a 40% to 50% volatile matter reduction and aerobic stabilization will achieve a volatile matter reduction of 30 % to 40 %. (CEN, 2001). Additionally, when anaerobic digestion is used, methane gas is obtained, and in most cases, it is used to cover a large percentage of the facility´s energetic needs. The treatment process a wastewater facility employs to stabilize the wastewater solids will result in either Class A or Class B solids depending on the methods used.

Anaerobic Digestion (AD) is a biological process involving the break down of organic matter by bacteria in environments with little or no oxygen. The biogas produced through AD is made up on its majority of methane (CH_4), as the main component (approximately 60 %) and carbon dioxide (CO_2) as balance (around 40 %), and other gases such as hydrogen present in less amounts. AD involves a series of complex biochemical reactions, but can be summarized in two big reactions: acidogenesis in which large chain compounds are broken into simpler compounds such as short chain organic acids, and methanogenesis, which involves the conversion of these compounds into methane and carbon dioxide (Metcalf, 2003, pg.1506). This process is highly dependent on pH, temperature and in hydraulic retention time.

Anaerobic digestion is an attractive option for several municipal wastewater treatment plants because biogas can be burnt to generate heat or electricity, and can partially fulfill the facility's energetic requirements.

Sludge Conditioning. After stabilization, the sludge is ready to be conditioned. Excess sludge is usually conditioned to improve its dewatering properties. The purpose of conditioning is to pretreat the sludge to improve the efficiency of thickening and the removal of water in ensuring further treatment processes and for ultimate use or disposal. Raw primary sludge is much easier to condition than digested or biological sludge. (ASCE & WEF, 1992; Kerri, 1994). Biological sludges are very hard to condition due to their complex nature. Some methods to improve dewaterability of biological sludges is to mix them with raw sludges. Further methods about sludge conditioning will be discussed in the sludge dewatering enhancement chapter.

Dewatering. The main purpose of sludge dewatering is to achieve a reduction in volume and in weight to improve it's handling. There is a limit to the amount of water that can be removed from sludge by mechanical means, and most dewatered sludge have dry solids content in the range 15 % to 40 %. (CEN, 2001). Further dewatering details will be discussed in the dewatering section.

Heat Drying. Involves the application of heat to evaporate water and to reduce the moisture content of biosolids below that achievable by conventional dewatering methods. By this method up to a 95% dry solids concentration can be achieved. However, a considerable amount of energy is used for heating (CEN, 2001).

Disposal. The most known techniques for sludge disposal are agricultural use, incineration and land filling, although this last one is no longer allowed in Germany since in 2005 it is no longer legal to dispose of materials with a total organic content (TOC) of more than 3%.

Land application is a method for sludge recycling in which it is used to supply plant nutrients and add organic matter to soil in agriculture (CEN, 2001). While the agricultural use of sewage sludge still represent a significant proportion of the total municipal sludge disposal in many countries (Spinosa, 2007), concerns on the possible risks derived from the presence of pathogens, heavy metals and organic pollutants in sludge (Harrison et al., 2006) tend to decrease the agricultural use and favor the incineration route, which consists on the reduction of the sludge mass carried out by a combustion of organics at high temperatures. (CEN, 2001).

In North Rhine-Westphalia, the percentage of municipal sludge used for agricultural purposes decreased from 33% in 2000 to 22% in 2005, while in this same period, the incineration rised to 64% from 39% in 2000 (LANUV-NRW, 2011).

In the future it is expected more rigid legislation on this matter, so that only good quality sludge will be disposed on agricultural soils.

3.6. Sludge Treatment at Beningsfeld Wastewater Treatment Plant

The mixed waste sludge (from the primary treatment and biological treatment) is pumped directly to the pre-thickener where it is thickened to levels up to 4% of dry matter. A gravity thickening is used, the thickener is comprised of slowly rotating rabble rakes, which further improve the separation of sludge from water. After thickening, the sludge is delivered to the stabilization process to reduce pathogen content through anaerobic digestion, this is carried out in two egg shaped anaerobic digesters with a volume of 3, 300 m^3 each (Figure 3) and a temperature of 37 ºC, with a production of approximately 5, 400 m^3 gas per day, in which two thirds are methane (CH_4) and one third is carbon dioxide (CO_2). This gas is pumped to a storage tank and is used for the facility´s heating station, were the whole plant´s heating requirements are fulfilled.

Figure 3. Anaerobic Digestors 1 and 2

In the Beningsfeld sewage treatment plant, the two digestion towers are fed with a flow of raw sludge of approximately 100 m^3/d. The average time the sludge is kept in the digester is approximately 35 days.

At the temperature of 37ºC (+/-2), the mesophilic bacteria have their highest activity. During digestion, approximately 60% of the organic sludge is converted into CO_2, CH_4 and water.

After the anaerobic treatment, further volume reduction is achieved by a "post" thickener, followed by a thermal treatment, were sludge's temperature is elevated to 180 ºC.

Some important parameters for a successful thickening are the retention time and pressure conditions in the thickener. The Beningsfeld treatment plant directs the sludge from the digesting towers into thickener 1, which serves as a storage tank for loading thickener 2.

Both thickeners have a volume of 600 m^3. Two eccentric screw pumps deliver the sludge from the first to the second thickener. The sludge initially has a dry matter content of 3% and is then concentrated to 6%. In thickener 2 the excess water is also removed. The thickener serves also as a storage tank for the sludge dewatering process. A final water extraction is achieved by two filter press. The dewatering process at Bergisch Gladbach is described on Chapter 4.

During the whole sludge handling process, the air is cleaned through a biofilter to prevent nuisance odors from going to the atmosphere.

With the sludge dewatering, the waste water treatment plant achieves a total solids concentration of 30% in the best of cases. The sludge is finally disposed off.

The plant produces 30 tonnes of sludge per day. An independent trucking service company removes the sludge twice a day and the total disposal costs of sludge can be up to 1 million euros per year (Retrieved from : Uwe, 2011, filter press operator at Bensberg WWTP).

CHAPTER 4. SLUDGE DEWATERING AND DEWATERING PROCESS AT BENINGSFELD WWTP.

4.1. Generalities

The main purpose of sludge dewatering is to achieve a high dry matter content and reduce the sludge volume to the highest possible extent. This is a necessary step in order to give a proper use to the sludge, as well as to reduce transportation and incineration costs.

The dewatering is achieved by continuous steps, it starts with thickening, where free water is removed, then chemical conditioning where the solid liquid separation in the sludge is improved through flocculating polymers, and finally, mechanical dewatering is done were a high solid concentration is achieved by compression.

The density and nature of the solid particles have a considerable influence on the thickness of the sludge produced. Sewage sludge contains highly compressible solids with relative density of about 1.4 and will only produce a sludge of 2-6 per cent solids. Attempts to increase the solids content by draining off excess water may cause the solids to compress, thus blocking the voids and preventing further drainage. Primary sewage sludge has a heterogeneous nature with fibrous solids so that drainage is easier than from activated and digested sludges which are much more homogeneous in nature (AWWA, 1989).

4.2. Gravity Thickening

"Thickening is the process by which biosolids are condensed to produce a concentrated solids product and a relatively solids-free supernatant. Thickening wastewater solids reduces the volume of residuals, improves operation, and reduces costs for subsequent storage, processing, transfer, end use, or disposal. For example, thickening liquid-solids (slurry) from 3 to 6 percent will reduce the volume by 50 percent". (EPA, 2003. pg. 1).

Gravity thickeners consist of circular tanks normally ending in a conical bottom, equipped with scrappers at the lowest point, which remove the thickened sludge and is collected into a discharge pipe. This type of thickening is easy to operate and uses simple equipment. Gravity thickening is usually employed before digestion to reduce digester volumes and it also helps to economize the requirements for subsequent sludge handling. (EPA, 2003). The mechanisms of thickening are carried out by different types of settling as shown on

Figure 4.

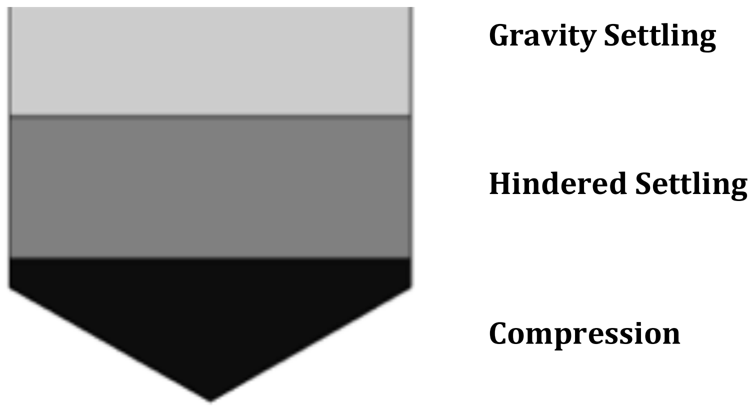

Figure 4. Thickening Mechanisms

(Modified from Bengt, 1998)

On gravity settling, particles settle freely due to their weight without interparticle interaction since it occurs under low solids' concentration. Then, in the hindered settling zone, there is a much higher concentrations of solids and the settling becomes slower, in this zone, particles remain in a fixed position with respect to each other and they still remain in suspension. Finally, on the deeper layer, compression takes place. At this point, the particles' concentration is so high that particles above exert mechanical pressure over the particles below promoting compaction. (Bengt, 1998; EPA, 2003).

"Solids at the bottom of the tank can be as high as 15 percent total solids (TS). A more typical result is 4 to 6 percent TS. Liquid at the surface of the tank is nearly clear, with suspended solids concentrations as low as 200 mg/L. The transition point between clear liquid and thickening solids that develops in the middle of the tank is called a "solids blanket." " (EPA, 2003 pg 2).

Thickeners are continuously in operation. During the settling process, floating sludge is lifted, and is moved by a clearing scraper into the side of the basin. The maximum time the sludge should spend in the thickening zone is 1 to 2 days. The period should not exceed 3 days in order to prevent rotting.

4.3. Mechanical dewatering

Solid–liquid separation by mechanical means, such as centrifugation, vacuum filtration and pressure filtration, is a common practice for sludge treatment.

The volume of the sludge containing as much as 99 per cent of water can be considerably reduced by mechanical dewatering. The resulting solid product can then be easily transported, treated or disposed. The efficiency of mechanical dewatering is largely dependent on the sludge properties and the effectiveness of sludge pre-treatment.

The filter press dewatering system will be broadly discussed in this chapter but first it is important to understand some theoretical concepts related to the filtering process therefore Filtration Cake Theory is briefly reviewed.

4.3.1. Cake filtration Theory

Cake filtration theory, also known as the conventional theory was developed by Ruth (1935) among other investigators, and it will be briefly discussed since it forms part of the basics in press dewatering and, although it is very theoretical, it helps to understand the mechanisms that take place on mechanical dewatering. It describes mathematically when a solid-fluid suspension is passed through a medium in which the water is allowed to flow while the solid particles are retained. It also describes how the cake thickness increases with the time spent on the filter, although it can also become more compact, affecting the flow of the drained water. (Chi Tien, 2003 pg 1323).

The cake filtration theory predicts the filtration behavior by stating a number of assumptions enlisted below:

1. The solid phase velocity is negligible.
2. The fluid velocity is constant across the cake at any instant.

3. The cake compactness, permeability and specific cake resistance are functions of the compressive stress only.
4. There is a negative relationship between the liquid pressure and the compressive stress. (Chi Tien, 2003, pg 1324)

The cake filtration theory consists on combining the mass balance equation and the momentum balance equation (or Darcy's law) for the liquid phase in the cake to elaborate the main equation including porosity and liquid pressure as dependent variables (D.J. Lee, 2000, pg. 2).

Chi Tien, 2003, compiled the main results on the Filtration Cake Theory and are shown on

Table 5.

Table 5. Filtration Cake Theory Equations (Chi Tien, 2003).

Basic equation: $q_\ell = \dfrac{k}{\mu}\dfrac{\partial P_\ell}{\partial x} = q_{\ell_m} \quad 0 \leqslant x \leqslant L(t)$.

Integrated results:

$$q_{\ell_m} = \frac{\mathrm{d}V}{\mathrm{d}t} = \frac{\Delta p_c}{\mu s \rho (1 - m_{\mathrm{av}} s)^{-1} \alpha_{\mathrm{av}} V} = \frac{\Delta p_m}{\mu R_m} = \frac{P_0}{\mu s \rho (1 - m_{\mathrm{av}} s)^{-1} \alpha_{\mathrm{av}} V + \mu R_m}, \quad \text{(a)}$$

where $\Delta p_c, \Delta p_m$ are the pressure drops across cake and medium,

p_0 the operating pressure, $p_0 = \Delta p_0 + \Delta p_m$

s the mass fraction of particles of the suspension

ρ the liquid viscosity

m_{av} the average wet to dry cake mass ratio

$$m_{\mathrm{av}} = [\bar{\bar{\varepsilon}}_s \rho_s + (1 - \bar{\bar{\varepsilon}}_s)\rho]/(\bar{\bar{\varepsilon}}_s \rho_s), \quad \text{(b)}$$

ρ_s the particle density

$\bar{\bar{\varepsilon}}_s$ the average cake porosity

$$\bar{\bar{\varepsilon}}_s = (\textstyle\int_0^L \varepsilon_s \,\mathrm{d}x)/L \quad \text{(c)}$$

α_{av} the average specific cake resistance

$$\alpha_{\mathrm{av}} = (\Delta p_c)/[\textstyle\int_0^{P_0 - \Delta p_m} (1/\alpha)(-\mathrm{d}p_\ell/\mathrm{d}p_s)\,\mathrm{d}P_s] \quad \text{(d)}$$

α the local specific cake resistance

$$\alpha = 1(k\rho_s\varepsilon_s) \quad \text{(e)}$$

Constant pressure filtration:

$$\mu\rho s\overline{(1 - m_{\mathrm{av}} s)^{-1}\alpha_{\mathrm{av}}}\,\frac{V^2}{2} + \mu R_m V = p_0 t \quad \text{(f)}$$

and $$\overline{(1 - m_{\mathrm{av}} s)^{-1}\alpha_{\mathrm{av}}} = \frac{2}{V^2}\int_0^V (1 - m_{\mathrm{av}} s)^{-1}\alpha_{\mathrm{av}} V\,\mathrm{d}V. \quad \text{(g)}$$

Constant rate filtration:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = q_{\ell_m} = q_{\ell_m} = Q = \text{constant}$$

$$V = Qt$$

$$p_0 = \mu Q[s\rho(1 - m_{\mathrm{av}} s)^{-1}(\alpha_{\mathrm{av}})(Qt) + R_m]. \quad \text{(h)}$$

Source: Table 1. Main Results of the Filtration Cake Theory pg.1325 Chi Tien, 2003.

As shown on

Table 5 from the integrated results, filtration is directly proportional to the operating pressure, this pressure usually does not exceed 16 bars, also, the sludge filterability, according to the theory, is dependent on the particle density. The moisture removal rate and the water content after dewatering also play an important role. Moisture removal rate is assumed to be controlled by the cake resistance to moisture movement, while the cake resistance to moisture is controlled by the capability for the solid phase in a cake to retain moisture against external mechanical pressures.

The conventional theory has had several applications for the design of sludge filtrating devices.

4.3.2 Filter press

Once the Cake filtration theory was concisely discussed, filter press dewatering will be described. It is also important to mention that there exist several other dewatering techniques, such as centrifugation, lagoons, sludge drying beds and reed beds, but will not be described since the focus of this study is mainly filter press dewatering.

In filter presses, high pressures are used to force water out of the sludge. Some of the advantages found for filter presses are the high solids concentrations and the filtrate clarity achieved. However, the main disadvantages are its mechanical complexity, use of chemicals, and limited cloth life which may increase costs over other dewatering methods (Metcalf and Eddy, 2003). The filter cloths are prone to clogging and therefore must be maintained or replaced at regular intervals. The filter cloths are usually made from polyamide and have a low water absorption capacity (ATV-Handbuch, retrieved from Hille, 2005).

In waste water technology the chamber filter press, suitable for all conditioning procedures, has prevailed. These presses consist of rows of filter plates, which are designed in such a way that each two adjacent filter plates form a closed chamber Figure 5.

Figure 5. Filter Press Beningsfeld Wastewater Treatment Plant

Filter plates are supported on side beams or suspended from an overhead beam; filter plates are squared, and they normally have a contact surface of 2.5 m^2 to 4 m^2 and larger plates are being developed. For wastewater sludge dewatering, 80 chambers in a recessed plate press or 60 chambers in a membrane plate press are common (Wakeman, 2007). In Beningsfeld WWTP, sludge is dewatered by two filter bed presses, each press consists of 72 plates (Figure 5) covered with membrane filter cloths, the cloths used will be later described.

Filtration is done in several stages. First, the filling period takes place, here sludge is pumped into the cavity at low pressure and it is fed through a mainstream pipe. The sludge is distributed in the various chambers until the hydraulic closing pressure is reached; the pumping rate controls the duration of this period. Second, the sludge cake is squeezed by inflating the membranes; then, a solid layer known as the filter cake is deposited on the filtration surface and grows without restriction until the whole chamber is filled. In some devices, this stage is referred to as the gravity stage as the filter cake is formed by gravity settling of the solids. Finally, the compression phase comes about. This increases the average solids concentration in the cake as a result of the pressure, a separation of solids and sludge water takes place on the filter cloths. In some dewatering devices, this stage is sometimes referred to as mechanical expression, because water is expressed from the filter cake by the application of pressure (Wakeman, 2007).

The longer the filter is fed with sludge, the bigger the filter resistance becomes. The duration of a filtration cycle is dependent on the sludge. From 10 to 20 minutes are needed to fill the press and another 15 to 30 minutes are required to press in order to have a relatively high solids content. (Metcalf and Eddy, 2003). In Beningsberg WWTP, a total filtration time of two hours is required.

The cake compression is affected by diaphragms that are pressurized up to 15 bars in the case of Bergisch Gladbach, in order to lower cake moisture content.

The reduction on the sludge's cake humidity content depends on its compressibility properties, on how well the water can be separated from it. The average percentage of dried solids obtained by filter press dewatering is of 25 per cent

According to Wakeman, (2007), one of the mechanical improvements done to increase filter capacity, dried solids content, and to reduce the time in the filter press are " (i) automation and mechanization of plate pack opening and plate shifting; (ii) use of long-travel hydraulic cylinders to move the pressure head to reduce press opening times ; (iii) cloth shaking or lifting mechanisms to promote cake discharge; (iv) cloth flushing or washing systems, which range from simple spray nozzles mounted above the plates to moving spray bars that are lowered and raised between plates singly or in groups, to remove adhering or penetrating particles (a limitation of most cloth washing systems is that only one side of the cloth is washed); (v) placement of the filter onto load cells to indicate if the filter fails to reach its tare weight (for filter control and/or throughput measurement); (vi) use of "bomb bay" doors to cover discharge chutes to prevent water entry into the dry cake handling facilities; (vii) light curtains and/or protective screens to prevent operator access". (Wakeman, 2007. Pg. 617).

There are several mechanical parameters that can be improved in order to obtain a better filter press performance. In terms of filtering time, although membrane presses are significantly more expensive than conventional filter presses, the additional capital and operating costs are often justified by shorter cycle times (and hence greater sludge throughput) and the more easily handled cake that is produced in the case of Bensberg WWTP.

4.3.3. Sludge characteristics that affect dewaterability on filter press devices.

There are great fluctuations in the quality of the sludge. Because the municipal wastewater composition can be variable, there is no sewage sludge alike, and this is an important factor affecting filter press performances.

Some parameters that affect the sludge's dewaterability on filter press devices are the following:

- *The composition of the sludge*. The sludge consists of a mixture of biosolids as well as organic and chemical particles and other ionic substances which may affect the cake resistance rate to filtration.

- *Pretreatment with flocculating agents*. The sludge's dewaterability on filter press can be greatly improved when pretreated with flocculating agents in order to facilitate the separation from water and to reduce the fine particle's content for they have a negative effect on filtration.

- *Type of sludge*. The filterability of the cake also depends on the type of sludge to be filtered. Sludge that comes from the biological treatment has a high biosolids content and may form wetter cakes, and the filtering rate is lower when compared with filtration of primary sludges under the same conditions of filtration.

Karr and Keinath, 1987, suggested that the main characteristics affecting sludge dewatering are the surface area of the divided particles, the nature and synthesis of the sludge particle surface, also, in case of biological sludges, the proteinaceous nature. (Retrieved from Huagaard, 2002)

- *The sludge age*. This is the time the sludge has spent in the activated sludge process, it is defined as the relationship between the mass of suspended solids (kg) and the mass of suspended solids added per day (kg/day).

(Wakeman, 2005 pg. 614-615).

Once the filter cake has been formed, there is also a great variability on their compressible nature and solid contents. The compressibility of the cake can be moderate to high. When there is certain compressibility on the sludge, this implies that further moisture can be removed by applying compressive force to the cake's surface.

The highest solids concentration is found in the membrane to cake interphase, at this point of the cake, a highly dried and stable mass of sludge is found, this part of the cake interacts very closely to the filter medium and can be bound to it, this bounding can later cause disruptions in the cleaning of the filter and cake removal from the membranes, causing the operator to employ a big amount of time cleaning the membranes manually.

This formation, is also called cake skin and is an inherent property of the cake, it is formed as a result of consolidation of the cake when sludge constituents are packed very tightly together due to a wide size distribution and deformation of components in the fed sludge. This cake skin causes a low permeability and a high pressure loss resulting in a high moisture content. (Wakeman, 2005 pg. 615).

The solids volume fraction in the cake (εs) and the specific resistance of the cake (α) can be related to the solids compressive pressure (ps) by the solids concentration.

$$\varepsilon_s = \varepsilon_{S,0}\left(1+\frac{\rho_s}{\rho_a}\right)^{\beta} \text{ and } \alpha = \alpha_0\left(1+\frac{\rho_s}{\rho_a}\right)^{n}$$

Equation 2

From Equation 2. The subscript 0 is the value of the solids volume fraction (εs) or the specific resistance of the cake (α) when compression is transmitted at first through the solid's network, "pa is a scaling factor, β and n are form constants that specify the degree of compressibility. When $n = 0$ the cake is incompressible; when $n < 1$ a cake has a low to moderate compressibility; $n > 1$ suggests a highly compressible cake (such as sludges from oxidation processes); $n= 1$ represents an extremely compressible cake (typical of biological sludges)". (Wakeman, 2005 pg.615)

Wastewater sludge cakes n values are equal or higher than 1, this means that they are highly or extremely compressible.

4.3.4. Possible economical benefits for Bensberg with increased sludge dried solids content.

At Bensberg waste water treatment plant a total of 7200 tones of sludge are produced each year, achieving a 25% dried solids concentration, meaning a total of 1,800 tones of dried mass. At the moment 48 euros per tone of dried sludge are paid for disposal by the plant. A total of 345,000 euros were paid on 2011 for the disposal of the sludge. (Thormeyer, 2011, director of Bensberg WWTP).

If the dewatering process were improved and a 28 % dried solids concentration would be achieved, 6,400 tones of dewatered sludge would be produced with a total disposal cost of 307,200 euros, this would represent an annual saving of 38,000 euros, when the dewatering process would be improved to 29% a total of 6,206 tons of sludge would be produced, with an annual disposal cost of 297,000 euros, this would represent a saving of 47,000.

This are the possible economical benefits that could be obtained by the facility if higher dried solids concentrations were achieved. However, in order to have further improvements, investment in investigation and material needs to be made. Knowing the possible benefits will allow the plant to have a better decision making, since the awareness of the maximum annual savings will help organize the budget and time spent on the enhancement of this process.

There are several techniques used to improve the dewatering process, which will be reviewed in the following chapters.

CHAPTER 5. SLUDGE DEWATERING ENHANCEMENT

Over recent years there have been several attempts to improve dewatering yields by means of sludge conditioning, either by physical, thermal, chemical and even by microbiological methods in order to obtain a higher percentage of dry solids. The following are some examples of physical and chemical dewatering enhancement techniques.

5.1. Physical Enhancement

Microwave irradiation. Quiang (2009) studied the effects of microwave irradiation on the dewaterability properties of the sludge; he tested capillary suction time and specific resistance of filtration. He found that sludge irradiation enhancement can slightly improve dewatering capabilities with short contact time. However, the sludge dewaterability properties were worsened with long contact times. Quiang found that the ideal microwave conditioning is at 900 Watts and contact time of 60 seconds. With these conditions the sludge is easily disintegrated and dewatered. (Quiang Yu, 2009 pg.88)

Skeleton builders. Skeleton builders normally consist on inert materials that can form a permeable and rigid structure in the sludge so that it remains porous during mechanical dewatering and more water can be drawn out of it. The most common skeleton builders reported by literature are gypsum, sludge with high inorganic solid content, ferric chloride, fly ash, cement kiln dust, quicklime, hydrated lime, fine coal, bagasse, wood chips and wheat dregs. (Y.Q. Zaho, 2002 pg. 206; Yin Qui, 2011 pg. 377; Benitez, 1994). Some of these agents may also be combined with polymers since they cannot contribute to a large improvement on sludge dewatering by themselves.

Electrical Enhancement. Xin Feng, (2009) found that with the application of an ultrasonic pretreatment with low specific energy dosages (<4400 kJ/kg TS) slightly enhanced sludge dewaterability. Also several researchers have tested electro-dewatering, which is a technology in which a conventional dewatering mechanism such a pressure dewatering is combined with electrokinetic effects to realize an improved liquid/solids separation (Mahmoud, 2010).

5.2. Thermal Enhancement

Heat treatment. In the temperature range from 40 to 180◦C (U. Kepp, 2000; M. Barjenbruch, 1999) the carbohydrates and the lipids of the sludge are easily degradable, the proteins are protected from the enzymatic hydrolysis by the cell wall. However, thermal pre-treatment in the temperature range from 60 to 180◦C destroys the cell walls and makes the proteins accessible for biological degradation. The input of thermal energy is mostly realized by heat exchangers or by application of steam to the sludge. (Neyens, 2003).

Freezing and thawing. By freezing and thawing activated sludge the floc structure will be irreversibly changed into a more compact form, the bound water content will be reduced and therefore the sludge dewatering characteristics can be significantly improved.

5.3. Chemical Enhancement

Chemical conditioning is used to destroy the frame of sludge colloidal particles, and flocculate the sludge. (Jianyong Lu, 2011).

Some chemical methods under research are the Fenton´s reagent, Ming Chung (2003) showed that ferrous and ferric ions can catalyze hydrogen peroxide to promote the filterability of sludge.

Another technique is electro-chemical conditioning. Hai Ping, (2011). indicated that application of considered low electrolysis voltages (<20 V) enhanced sludge dewaterability.

Aditionally, Yinguang (2001) investigated the use of acids and surfactants and the effect of pretreating activated sludge with sulfuric acid and surfactant on dewaterability and settleability and showed that the centrifugal dewatering efficiency was increased with the decrease of sludge pH value, and which was further improved if the surfactant was simultaneously applied.

Co-conditioning, is another technique in which waste activated sludge is mixed with the chemical sludge, normally at ratios of 1 : 1 and 2 : 1, respectively, the dewaterability of chemical sludge is improved while the relatively better dewaterability of the waste activated sludge may be deteriorated (G. R. Chang, 2001).

Chemical treatment using ozone, acids or alkali has been tested (Tanaka,1997; Sakai, 1997). It is found that with these treatments, barely degradable compounds are converted into easily degradable ones.

Liu et al. (2001), consider advanced oxidation processes (AOPs) as valuable sludge pre-treatment. These processes also enhance dewaterability of sludge (A. Mustranta, 1993).

Another chemical enhancement method recently developed is the Kemira conditioning process (Kemicond). The main objective of the Kemicond process is to improve the dewaterability of sewage sludge by altering the sludges' structure through treatment with sulphuric acid followed by oxidation with hydrogen peroxide. This process also has the possibility of recovering coagulants and flocculants. It was first studied in Darmstadt (Germany) and Helsingborg (Sweden) over digested sludge, and its dewaterability was improved to the degree that in some cases, it was no longer necessary to use further conditioning with polymeric flocculants (Cornel et al., 2004). This process will be further described on Chapter 9, since some trials were carried out to test the efficiency of this pretreatment.

Finally, the use of flocculant polymers has been widely used for the separation of water in the sludge. The addition of polymers helps to aggregate fine solids and also improves the permeability. (Sharna M. Glover, 2004 pg. 145). They are highly effective when used prior to press filtration. The dewaterability is noticeably higher when polymers are added. The following chapter intends to present the main polymer flocculants used for the dewatering of sewage sludges.

CHAPTER 6. DEWATERING FLOCCULANT POLYMERS

Before discussing the different flocculants, it is important to know the flocculating mechanisms, and how these polymers work.

6.1. Flocculation Mechanisms

First of all it is important to know some general facts about sludge colloidal particles. They are normally negatively charged and stable in suspension and do not aggregate between each other. Their separation from water is rather difficult because of their small size therefore they must be aggregated. The aggregation of colloidal particles is done by two different mechanisms. First coagulation which refers to the process by which particles are destabilized or their charges are neutralized in which net repulsion force, also considered as energy barrier, must be overcome before aggregation occurs. The magnitude of energy barrier depends mainly on charge on the particle, and on ionic composition of water.

The final aggregation between particles is called flocculation. To have a better understanding of the coagulation-flocculation mechanisms it is important to review the electro-neutrality of a colloidal particle, represented by the double layer theory.

Electrical Double Layer. "Colloid particles carry electrical charge, the requirement of overall electro-neutrality of the interfacial region results in the formation of a diffuse layer of oppositely charged counter-ion adjacent to the particle surface, and thus the formation of electrical double layers". (Su-zhen Li, 2008. Pg.158). The electrical double layer is represented on Figure 6 and charge distribution in the diffuse layer of a negatively charged colloid is shown on curve ABCD on Figure 7.

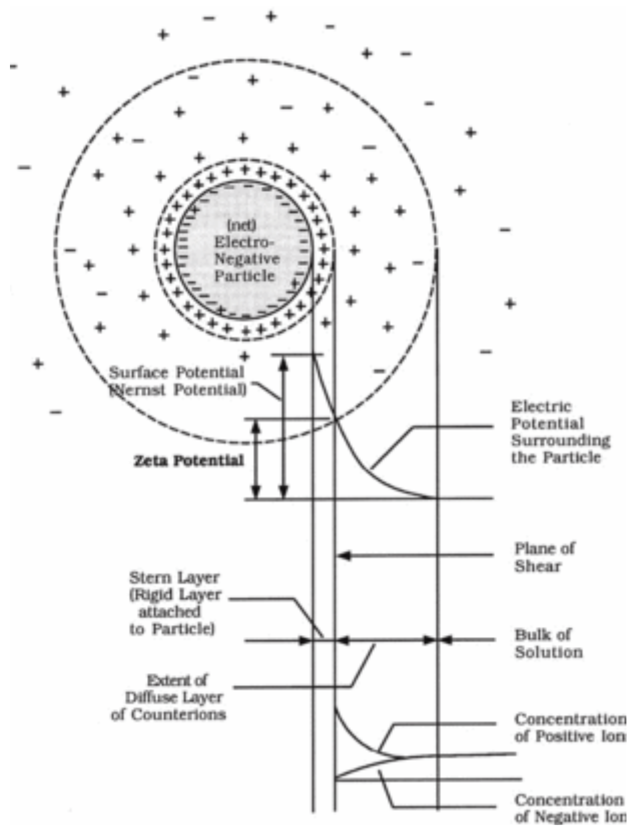

Figure 6 Electrical Double Layer

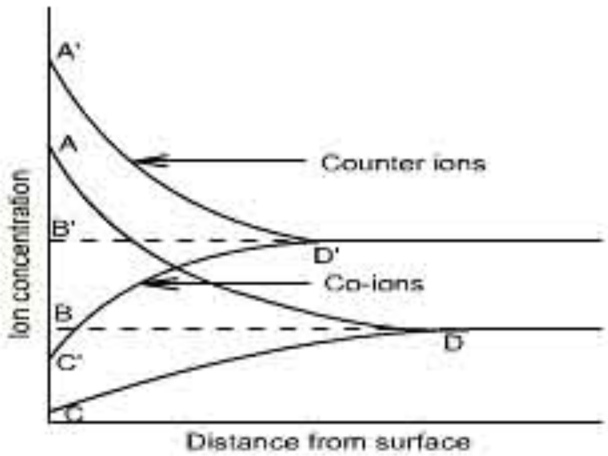

Figure 7. Electrical Double Layer

(Source: NPTEL, 2003)

There exist several mechanisms by which destabilization of colloidal particles are carried out:

- **Compression of the double Layer.** This is when colloidal systems are destabilized by ions with an opposite charge to the system. The precipitating action of ions of opposite charge to those of the surface of the particle is greater the higher the valence of the ion (Schulze-Hardy rule).

- **Adsorption and Charge Neutralization.** The surface potential is reduced by the addition of sorbable species of opposite charge to that of the colloids, they can destabilize the system at lower dosages than those that compress the double layer. An interesting fact of this type of destabilization is that the system can be overdosed, this means that the colloidal particles can be again stabilized by reversal of charges.

- **Provision of Bridges.** The provision of bridges can be done by Sweep flocculation and interparticle bridging. On sweep flocculation, the ions generate bridges and the colloidal particles are carried or enmeshed as the coagulant network settles. However, on adsorption and interparticle bridging, polymers, either negatively or positively charged are capable of destabilizing the particles by adsorption at optimal dosages. (NPTEL, 2003)

Once the flocculating mechanisms were understood the different kinds of polymeric flocculants that are used for sludge dewatering will be described in the following sections. Polymers can be classified into two wide groups inorganic and organic polymers, within the organic polymers we can also find synthetic and natural ones.

6.2. Inorganic Flocculants

Inorganic chemical conditioning is associated principally with vacuum filters and pressure filter presses. The most common practice is to use chemicals such as ferric chloride alone or in combination with lime. The addition of these chemicals to the sludge reduces electrostatic repelling forces and allows the solids to coagulate and flocculate into a heavier mass. Positively charged metal ions are responsible for the destabilization of negatively charged particles. The stronger the effect of the disruption of the hydrate sheath from the sludge particles, the better the dehydration of the sludge and the water discharge (Stier, 1990). They allow a better filterability by coagulating the colloids (thus lowering the content of linked water) and by micro-flocculation of the precipitates (hydroxides).

Iron and Aluminum salts

The dosages for iron salts are between 3% and 15% of the dry content, depending on the quality of the sludge. However the optimum ferric chloride and lime dosages for sludge conditioning depend on the sludge characteristics. In general, ferric chloride dosage ranges from 2-10% of solids and lime ranges from 5-40%, both based on dry solids (ASCE & WEF, 1992). Normally, 2 and 3-valent metal salts ($FeSO_4$, $FeCl_3$, $NaAlO_2$) are used for flocculation. However, the addition of metal salts alone is not enough to obtain a satisfactory filtration result.

The main disadvantages of this type of flocculants are the following (B.R. Sharma, 2006 pg. 196):

I. A big amount of flocculant is required in order to achieve solid-liquid separation and a greater amount of sludge is produced which later on needs to be disposed off.
II. The system has a high dependence on pH.
III. They normally do not coagulate very fine particles.

Lime

Lime as a conditioning agent only used in conjunction with iron salts on filter press applications. It brings a mineral nature to the sludge and strengthens its mechanical properties (higher specific resistance to filtration). The dosages for lime are between 15% and 40% of the dry content.

Some important remarks about lime are the following (SNF Floerguer, 2003):

I. Lime is also used after dewatering to stabilize the sludge.
II. The specific resistance to filtration (r) depends on the size, shape and degree of agglomeration of the solid particles that make-up the cake from a filter-press. It is independent of the sludge concentration.

Only with the addition of hydrated lime ($Ca(OH)_2$) sufficient conditioning can be obtained. All parts of the sewage plant that come into contact with the conditioning solution must be made of corrosion-resistant materials.

A good dehydration result is achieved at a pH of 7. Sometimes it is necessary to raise the pH to 7 by higher addition of lime.

6.3. Organic Flocculants.

One of the greatest improvements on solid–liquid separation in recent years is the development of organic polymers with remarkable abilities to flocculate sols even when added in small quantities (ppm). They came in use some thirty years ago. Organic polymers flocculate using mainly two mechanisms, destabilization of colloidal systems by charge neutralization and interparticle bridging. A polymer can adsorb on the surface of a colloidal particle as a result of either chemical forces (e.g. chemical bonding due to charge) or physical force (e.g. van der Waals force), or both. (Ying Qui, 2011 pg. 381)

These are primarily organic water-soluble polymers of high-molecular weight, produced either from natural raw materials or synthetic products. Organic flocculants can be further characterized depending upon the nature of monomer present in a polymer. If a monomer in a polymer contains ionizable groups (carboxyl, amino, sulphonic etc.) the polymer is termed as polyelectrolyte. On the basis of the ionizable groups on the monomeric units, a polymeric unit can be cationic, anionic or ampholytic. Thus based on charge, flocculants are divided into four categories : non-ionic, cationic, anionic and ampholytic. (B.R. Sharma, 2006 pg. 196).

Depending on their origin, they can be classified in one of the following groups: Synthetic Organic Flocculants or Natural Organic Flocculants.

6.3.1. Synthetic organic flocculants

These types of flocculants are based on various monomers like acrylamide, acrylic acid, diallyldimethyl ammonium chloride (DADMAC), styrene sulphonic acid, etc. They are effective and flexible due to tailorability of the polymers. Several characteristics can be modified, such as molecular weight distribution, nature and percentage of ionic charge and the structure of the polymer itself can be varied.

Sludge is found to be negatively charged (approximately -30mV), and hence cationic synthetic polymers are generally employed to neutralize the sludge charge, which facilitates the sludge settling and dewatering (Changa et al., 2002).

Polymers are usually added to the sludge in emulsion and they are diluted, otherwise the molecules are unable to exert their full effect. The grain size of the polymer is between 0.1 - 2 mm. Even with organic polymers, it is necessary to equip all plant parts with corrosion-resistant materials (ATV-Handbuch).

Polyacrylamide based flocculants are highly used for sludge dewatering. Polyacrylamide (Molyneux 1983) has an unusually high molecular weight (3 to 15 million number-average MW), it is also very hydrophilic and of nonionic nature. Its nonionic character is often modified by chemical conversion to cationic and anionic forms. Conversion of PAM to ionic forms begins to occur in aqueous solution at neutral pH at about 67ºC, where the amide groups are hydrolyzed to carboxylic groups. (Daughton, 1988). Anionic forms are formed by hydrolysis of the amide group to a carboxylic group; the degree of hydrolysis varies immensely among polymers (up to 50%). As for cationic polyacrylamide several methods have been developed for its production such as homogeneous aqueous solution polymerization, inverse emulsion polymerization, inverse suspension polymerization and dispersion polymerization. (Daughton, 1988 pg.3).

Typically, cationic polyacrylamide is used as a sludge conditioning agent, due to its high solubility, high molecular weight and the presence of several polar groups in the molecular chain which habilitate it to form bridges among particles and agglomerate particles into big flocs by neutralizing charges. (Zhengzhou Zhengli Polymer Technology Co., Ltd., 2011).

When polyelectrolyte conditioning is conducted, there is no change in the natural sludge texture and therefore no decontamination takes place. For the removal of the conditioned sludge it is advantageous that, when organic polymers are used, the amount of dry matter does not increase. Despite the great dewatering yields obtained through this types of polymers, the addition of polymers generates the addition of large quantities of water. This type of dewatering agents are also rather expensive. Another draw back of this type of polymers is that they are non-biodegradable and toxic to the environment. Recently has acrylamide received attention as a possible toxicological problem since it is present as a residue in water treatment. Acrylamide residuals are not only environmentally unacceptable in discharge waters, but in industrial reuse operations they can be deleterious to down-stream processes. (Daughton, 1988 pg.3).

Therefore it is important to explore the natural alternatives in order to be prepared for future rigid regulations on sludge disposal with non biodegradable compounds.

6.3.2. Natural organic flocculants

Natural organic flocculants are normally based on natural polymers like starch, cellulose, natural gums and mucilages and their derivatives. They have a high molecular weight with a fixed molecular constitution and chain length, most of them are modified in order to obtain flocculants with good properties, even though most of the technologies for their production are still complicated and not very rentable. Chapter 7 presents a review on the main natural possibilities that can be used to improve sludge dewatering.

CHAPTER 7. NATURAL DEWATERING AIDS

7.1. Starch derivatives

Starch is originated form several plants, it is a polysaccharide joined by glucosidic bonds and can be used as a renewable resource in several applications. Natural starch is made up of two glucose polymers, amylose and amylopectin. (Xing, Guo-xiu, et al., 2005, pg. 13). It is of low molecular weight ranging from 10,000 to 60,000 g mol. (S. Pal, 2005, pg. 417)

Among other applications, starch has been widely used as flocculant; however it needs to be modified to improve its efficiency. Starch can be chemically modified by reacting it with hydroxyl groups or grafting with other polymers. This provides more flexibility and broadens its usefulness as flocculating agent. (Xing Guo-xiu, et al., 2005 p.13).

Graft polymers produced by the reaction of starch with cationic, anionic and nonionic acrylic monomers show considerable potential as flocculating agents for treatment of wastewaters and for retrieving certain metals. Performance of the polymers depends on the nature of the system being treated and on the structure of the starch grafts. Percent add-on, grafting frequency, molecular weight of grafted chains and ionic charge are important variables in starch graft polymer structure that influence performance. Effectiveness of the polymers as flocculants has been demonstrated in laboratory tests and at on-site trials. (Burr et al, 1975).

Another method for starch modification is using microwave-assisted synthesis. It has a higher conversion pace compared to the traditional modification modes. Also, this method requires less time, reactions can be achieved in minutes in comparison with the conventional grafting methods which require hours or even days. This might help energy saving. Additionally it does not require the use of solvents, providing a great environmental advantage (Y.Wei, 2008, pg. 674).

Cationic starch derivatives

When highly negatively charged colloids need to be removed from a suspension, cationic starch is used. Cationic starch is obtained combining the parent starch with positively charged groups such as amino, imino and ammonium groups. They can work on a high pH range and they are highly biodegradable (S.Pal, 2005, pg. 418).

The following schema shows the modification routes for cationic starch derivatives

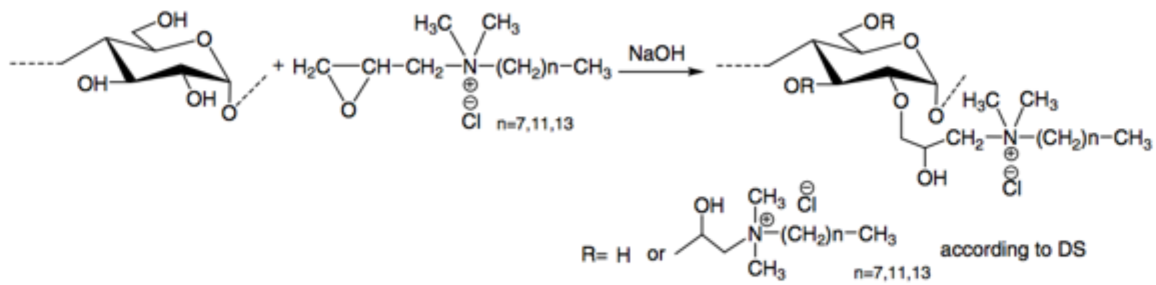

Figure 8. Synthesis route of cationic starch derivatives

It is a natural alternative, although a drawback on its application is that it is obtained from several staple foods such as potato, wheat and maize.

7.2. Chitosan flocculants

Another natural biopolymer with great application to wastewater treatment is chitosan due to its polycationic nature. It is obtained from chitin which is a biopolymer extracted from shellfish and other crustaceans, and it is the second most abundant natural polymer in the world, only after cellulose. It is biodegradable and non toxic. However, chitosan, on its natural form its soluble in water only in certain pH ranges, it is no longer soluble in pH over 8; therefore, like in the case of starch, chitosan, also needs to be modified in order to make it more flexible and make it soluble in wider pH ranges. (Zhen Yang, 2011 pg.2)

Amphotheric chitosan has been widely used in wastewater treatment. It also has potential to be used as dewatering aid since it is a rather flexible material, which can neutralize charges of anionic or cationic substances. It can flocculate thick masses of sludge. It is generated through grafting chitosan with vinyl monomers because of the composition of chitosan which has a large number of amino and hydroxyl groups which can react with vinyl monomers without using a large amount of energy. Modified chitosan has the advantage of being easily biodegradable because of the parent material, and also has the flexibility of synthetic polymers. (Jian-Ping Wang et al., 2007).

Some of the chitosan flocculant providers are Hild and Associates Inc. their chitosan product is called Biostar CH with 1%, 2% and 3% solutions. They have a wide range of presentations, although the 275 gallon totes are the most cost effective and suitable for large scale treatment, the treatment plant has the equipment necessary for its transportation, and due to the volume of treatment it would be suitable for it. In Germany, another supplier of chitosan flocculant is BioLog Biotechnologie und Logistik GmbH, it supplies chitosan under the category of biological cationic polymer. It has a supply capacity of 8 tons per month in bags of 125 kg. Price of chitosan flocculant ranges between 16 and 25 USD per kilogram.

7.3. Microbiological flocculants

Microbial flocculants (MBFs) are produced by microorganisms and are normally comprised of macromolecular substances that can flocculate suspended solids, cells, and colloidal solids. They have high efficiency, innocuity and biodegradability over traditional flocculants (Zhang, 2010, pg. 247). The production of this bioflocculant implies the use of microbial technology, for its extraction from certain bacteria, algae and fungi. This type of flocculants are easily biodegradable, have a high flocculating performance and generate no secondary pollution. They are mainly produced by microbial metabolism from various types of polysaccharide, protein, and carbohydrates, lipids, RNA and DNA involved in the formation of polymers. Microorganisms can produce several kinds of microbial flocculants, which abound in the soil, activated sludge and sediments.

Microorganisms are capable of growing in diverse environments producing secondary metabolites during their growth, mainly consisting of carbohydrates (Extra Cellular Polysaccharides, alginate and chitosan), proteins (lectins), lipids (fatty acids) and DNA & RNA, also denominated exopolymeric substances (EPS). It has been well documented that microbial EPS play an important role in bioflocculation process by interacting with the sludge solids. The microbial EPS may be non-ionic or may contain cationic, anionic and/or both charges (Garnier et al., 2005, retrieved from Subramanian, 2010 pg. 157).

7.3.1. Extracellular polymer substances (EPS)

The mechanisms through which microbial flocculants work, is through extracellular polymer substance (EPS). They operate as glue in forming aggregates or bioflocs. They can form aggregates through chemical cross-linking and physical entanglement. EPS may stabilize the floc structure by developing gel-networks surrounding the solid particles in the sludge. There are two types of binding mechanisms between water molecules and the EPS structure electrostatic interactions and hydrogen bonds. (Katja, 2007)

EPS can be originated not only from metabolic excretion of microorganisms, they can also be formed from wastewater from the adsorption of organic matter (cellulose and humic acids). (Haakarainen, 2007. pg. 97, 98).

There have been identified two types of EPS which play an important role in sludge dewatering, they are slime and capsular EPS. Slime EPS are washed out from cell during centrifugation or harvesting while capsular EPS are stable and attached on the cell wall of microorganisms. (Subramanian, 2010, pg.158).

It is also important to note that EPS can also retain water within their structure and they need to be sometimes oxidized by chemical or thermochemical processes in order to reduce their water retention capabilities so they do not disturb the dewatering process.

7.3.2. Bioflocculant producing microorganisms

Several microorganisms have been isolated for their flocculant production. Most of them are isolated from soils and from activated sludge, some examples of this microorganisms are listed below.

Agrobacterium sp. M-503. It was isolated from activated sludge of propylene epoxide wastewater treatment. The yield of the bioflocculant reached 14.9 g/l at batch cultivation. It was characterized by Qiang Li, et al, 2010, and the flocculant produced by this bacterias was found to be a low molecular weight polysaccharide on its purified form. It showed high pH and temperature stability.

Bacillus licheniformis X14. This microorganism was mainly tested for drinking water treatment, however it proved to have good flocculating yields, removing a high percentage of turbidity and COD, so its applications can be wider. It was isolated from soil. (Zhong Li, et al. 2009).

Chryseobacterium daeguense W6. This microorganism produces an intracellular flocculant, it was characterized by WeiJie Liu et al. (2010). It was isolated from a backwashing sludge from a biological aerated filter. This type of flocculant is mainly composed of protein and polysaccharide and in a lower proportion of nucleic acids, its highest flocculating rate was 97%.

Citrobacter sp. TKFM. It was isolated from a biofilm formed in a kitchen drain. It can utilize acetic or propionic acids as the sole carbon sources for bioflocculant production. It produces a bioflocculant similar to chitin, and the optimal dosage concentration was found to be of l-10 mg/l, over a wide range of pH (2-8) and temperatures (approximately 3-95ºC).

Corinebacterium glutamicum. This microorganism was screened from activated sludge and from soil. It was characterized by Ning He et al, 2002. It is believed that it is produced by biosynthesis, and the greatest flocculating yields were observed in the early stages of the cell growth and it was degraded at the later stages. Its flocculating capacity was of 80%.

Serratia ficcaria. A flocculant produced by this microorganisms was described by Wen-Xing-Gong, et al., 2008. This microorganisms can be isolated from activated sludge or soils. Its flocculation efficiency was found to be of 95.4%.

Several other strains, such as bacillus, pseudomonas, and fungi have been reported in the literature to act as effective flocculants (Hyun-Hyo Suh, 1997. Anuradha Mishra, 2006; Bin Lian, 2008. I.L. Shih, et al. 2001). This type of flocculants have been widely used for sludge settling, and for decontamination of large water bodies such as rivers and lakes, but little has been studied about their dewaterability capabilities. However, some of this biological flocculants have been tested as substitute for polyacrylamide which is a common polymer used in sludge solid-liquid separation; therefore, they might have potential as dewatering aids. Only one study has been made by Zhiqiang Zhang (2010), testing a strain of microbial flocculants for sludge dewatering conditioning: *Proteus mirabilis* TJ 1; it was screened from mixed waste sludge from four wastewater treatment plants in Shanghai, China. The Buchner Funnel test and specific resistance in filtration were used to measure dewaterability. This microbial flocculant has proven to improve sludge dewatering; it was combined with another cationic polymer, and the optimal ratio using both dewatering aids was of 3:2 for TJ-F1/P(AM-DMC). Zhiqiang also found that the dewaterability of the sludge is better than that obtained when using only one of the conditioners.

CHAPTER 8. PROBLEM DESCRIPTION AND SPECIFIC GOALS

One of the main bottlenecks at Beningsberg wastewater treatment plant is the handling of the sludge. Annually, the sludge disposal costs for the plant oscillate around one million euros. It is necessary for the plant to optimize the dewatering process, by optimizing the use of coagulants, adequate maintenance of the equipment, frequent monitoring, and use of best available products in the process to obtain better-dried solids results.

There are several problems involving this step of the sludge treatment in the facility. There is a great variability between the performance of the filter press, and the homogeneity of the sludge. Regular yields are obtained with the mechanical dewatering, with a total solid concentration oscillating between 24-29%, and the solid content can vary within one day and within different points at the same press.

It is important to know the origin of the variability on the sludge characteristics, also, to know the key factors that affect the sludge overall dewaterability results.

The main objective of this research was to define the main parameters that affect the overall dewaterability performance in terms of dried solids, and what are the possibilities to improve this process at Beningsfeld Wastewater Treatment Plant.

In order to achieve this main objective, the following goals were stated:

Define the critical points of improvement for the chemical and mechanical dewatering process.

Describe the plant's sludge in terms of its rheological properties such as viscosity, temperature and pH, and relate them with a dewaterability parameter by capillary suction time (CST) testing.

Test the performance of the filter press by testing the percentage of dried solids at different points of the press.

Define the optimal dosage of the current polymer in a lab scale level using the CST test, and in the full scale with trials carried directly in the filter press.

Reactivate small press (Smith, 2008), for further pilot scale studies, although this objective was partially accomplished.

CHAPTER 9. ANALYTICAL METHODS.

9.1. Total Solids Analysis

This method quantitatively determines the percent total solids, including organic and inorganic material, based on gravimetric loss of volatiles on heating. This method does not remove molecular bound water.

Total solids (TS) percentage was determined gravimetrically based on the loss of volatiles and free water, were approximately 15 g from each sample was placed into a ceramic glass and heated in an oven at a temperature of 105 ºC until mass remained constant, which was within a period of 20 to 24 hours. Figure 9.

Figure 9. Determination of dried solids

After the samples were removed from the oven, they were cooled for three hours, and the samples final weight was measured. The difference in weight was registered and the total solids content as percent (%) was estimated according to the following equation:

For primary results given in g:

$$TS = [(Wd - Wp) / Ws] \times 100\%$$

Equation 3.

Where TS is the total solids content of the unknown or control (%); Wd is the total weight of the unknown or control including the weighing dish, after drying (g); Wp is the tare weight of the weighing dish (g); Ws is the weight of the unknown or control, before drying (g) (Holstege, 2010)

All of the samples taken from the filter press were submitted to solids analysis.

9.2. Viscosity

The viscosity (η) is a useful parameter for the rheological properties of biological sludges, and it is defined as the ratio of shear stress over the shear rate for a Newtonian fluid. It normally varies with temperature and its units in the international system are pascal-second (Pa·s), which corresponds exactly to 1 $N \cdot s/m^2$ or 1 kg/(m·s). (Widman, 2009), although it can also be measured in Poise (P) or centi Poise (cP).

Viscosity is measured by establishing the necessary force (cutting or shear effort N/m^2) to move the particles of material g with a particular distortion speed gradient, (S-1)). Viscosity (h) is obtained as a result of the ratio between the cutting effort and the speed gradient. Since the sludge is a Newtonian fluid, viscosity measurement depends on the spindle and velocity in revolutions per minute (rpm). It is important to relate the rheological characteristics of sludge to its water content, and dewaterability capability.

The first viscosity measurements were made with a Rotational viscosimeter HAAKE VT 02 ®. The measuring device is composed of three different measuring scales, as shown in the following table.

Table 6. Viscosity scale

Spindle	Viscosity (η) in Pas	
	Lower scale	Upper scale
3	0,03	1,3
1	0,3	15
2	10	4000

The measuring device 3 was used to carry out the experiments for the primary and the activated sludge viscosity, since it oscillates between this scale for both types of sludge. The temperature was fixed at 20 ºC, since there are visible variations with the change of temperature, and sometimes the sludge was warmer than others, so the temperature parameter was fixed. The volume of the sludge used was of 300 mL, and the sludge was previously stirred.

Figure 10. Viscosity Measurement with HAAKE VT 02

Later on, the HAAKE VT 02 ® viscometer Figure 10 , was substituted for an R model Selecta STS Rotational viscometer ® Figure 11, this is a digital viscometer also used to measure dynamic viscosity, with a measuring range of 100 to 13,000,000, c Poise, an extra spindle was adapted to measure lower viscosity with a ranges from 0 to 100, with a precision of ± 0.1. This was used for primary sludge measurements.

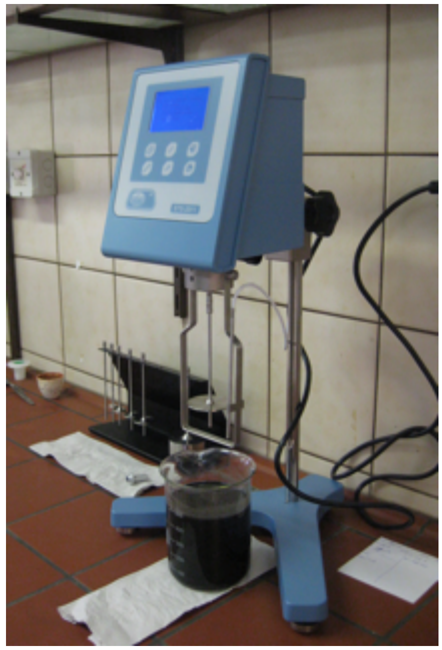

Figure 11. Viscosity Measurement with Selecta STS Rotational Viscosimeter ®

The viscosity was measured using 500 ml samples on 600 mL flasks to allow the spindle's mobility. Once the spindle is introduced into the sludge up to the spindle's reference mark, the spindle starts rotating according to the established velocity, which can be from 0,3 to 100 RPM. The speed normally established for the sludge is 60 to 100 RMP, after a minute of rotation the viscosity and temperature lectures were taken in cP and in ºC respectively.

9.3. Capillary Suction Time Testing.

Optimizing chemical dosages is not only important to the dryness of the cake, but it also affects the solids capture rate and solids disposal costs. Several types of tests can evaluate the effectiveness of a single conditioning chemical or group of conditioning chemicals. Standard test procedures include jar tests, CST tests, Buchner funnel tests, and pilot-scale and on-line testing.

The capillary suction time (CST) test involves measuring the time to move a volume of filtrate over a specified distance as a result of the capillary suction pressure of dry filter paper. The CST test provides information regarding the ease of separating the water portion from the solids portion of sludge. (Aarne, 1988).

The CST is typically defined in units of time (seconds). For, example, the typical range of CST for unconditioned organic wastewater sludge is 100 to 200 seconds (EPA 1987). In general, to dewater this type of sludge in a filter press, a CST of 10 seconds or less is required. (Aarne, 1988).

A HeGo Biotec® capillary suction timer was used for the tests; 4 mL of sludge were taken with a plastic bulb and poured into the cylindrical device as shown in Figure 12. The lecture was taken directly from the electronic screen.

Figure 12. He Biotec ® Capillary Suction Timer

9.4. pH Measurement

The pH or hydrogen potential is the concentration of hydrogen ions, it is a measurement of the basicity or acidity of an acqueous solution, and it is defined as follows:

$$\mathrm{pH} = -\log(c\mathrm{H}/c°)$$

Equation 4

where cH is the hydrogen ion concentration in mol dm^{-3}, and $c° = 1$ mol dm^{-3} is the standard amount concentration. (IUPAC,2002 pg. 2172).

Measurement of pH was done with an automatic pH meter device calibrated with distilled water. The sludge samples were measured directly with the pH sensor. Figure 13.

Figure 13. pH Meter device

CHAPTER 10. SMALL SCALE TRIALS

The plant's sludge was described according to its rheological properties. Different types of relationships were constructed to observe weather the sludge's dewatering capability, measured through capillary suction time, was dependent on temperature, viscosity and polymer dosage.

10.1. Sludge Characterization

10.1.1. Relationship between temperature and viscosity

A sample of sludge from the anaerobic digester was taken; the relationship between the temperature and the viscosity of the sludge was constructed with temperatures of 23, 31, 40, 50 and 60ºC. The first measurement corresponds to the ambient temperature, and higher temperatures were achieved by heating the sludge in a mixing and heating plate. The viscosity was measured according to subchapter 9.2, with the digital viscometer procedure.

Table 7. Sludge Temperature and Viscosity

Temperature ºC	Viscosity (1min)mPs
23	816
31	570
40	389
50	265
60	76

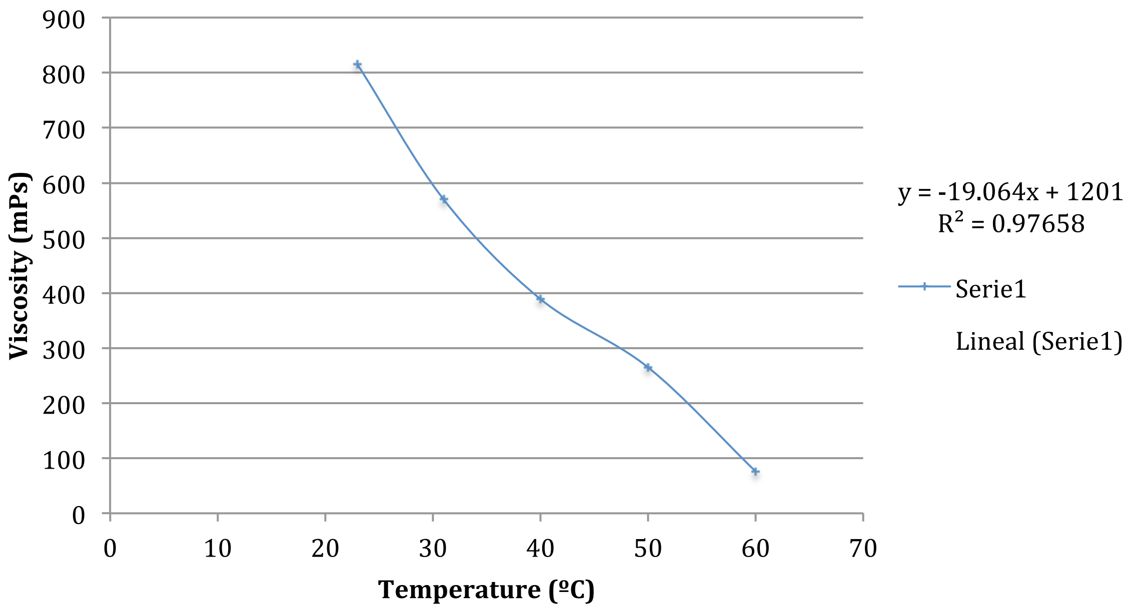

Figure 14. Sludge Temperature vs Viscosity

Figure 14 shows an expected inverse relationship between the sludge's temperature and its viscosity. At ambient temperature (23º C) a viscosity of 816 mPs was registered, when the temperature was raised almost three folds (to 60ºC) the viscosity decreased almost ten times to 76 mPs (Table 7). This shows how temperature has a high effect on the sludge's rheological properties. Additionally, it was important to relate temperature and viscosity to the sludge's capability for dewatering, so this parameters were also related to capillary suction time values in the following subchapters.

10.1.2. Relationship between capillary suction time and viscosity with and without polymer dosage

A relationship between the viscosity and the capillary suction time was built in order to obtain information about the sludge's rheological properties and its dewatering capabilities. A mixed sludge sample was taken from the anaerobic digesters 1 and 2, and it was divided in samples of 500 ml each. First, the sludge's behavior was tested without polymer dosage and its CST and viscosity values were obtained at different temperatures.

The results from this trial are shown on Figure 15, with its corresponding data on

Table 8. The blue plot represents the relationship between temperature and capillary suction time, whereas the red plot represents the relationship between temperature and viscosity, later on, the relationship between CST and viscosity is described.

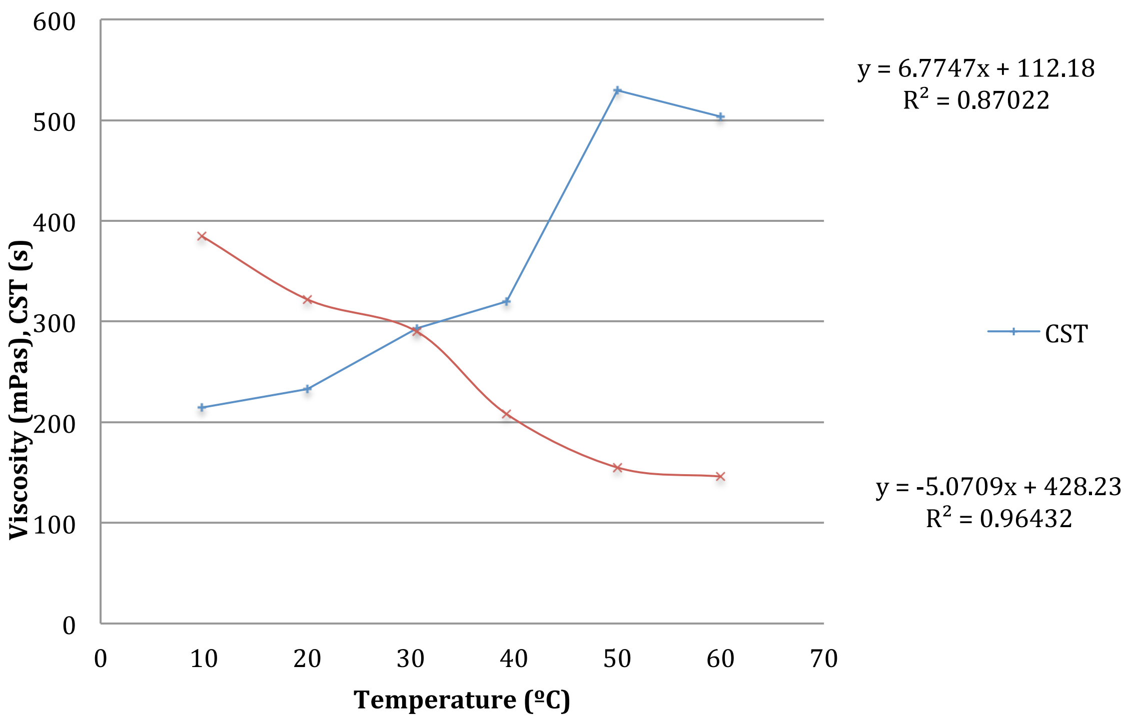

Figure 15. Relationship between T and CST and Viscosity without polymer

Table 8. Data values corresponding to Figure 15

Temperature (ºC)	9.8	20	30.6	39.3	50	60
CST (s)	214.2	232.6	293.4	320.2	529.5	503.8
Viscosity (mPa.s)	385	322	290	208	155	146

From Figure 15, it can be observed again an inverse relationship between temperature and viscosity, as for the capillary suction time, it is affected by temperature and viscosity. The CST values on the digested sludge without polymer dosage vary from 214 seconds at temperatures around 10ºC until 503 seconds for the highest temperature tested (60ºC). There is a direct relationship between capillary suction time and temperature which is represented by the following equation with a r^2 value of 0.87:

$$CST = 7\ T + 112$$

Equation 5

For viscosity and temperature the following relationship was found:

$$Viscosity = -5\ T + 430$$

Equation 6

Combining equations 5 and 6, a relationship between CST and viscosity can be obtained, and it shall be represented as follows:

$$CST = -7/5 Viscosity + 714$$

Equation 7

These relationships serve only to give a rough idea of how temperature influence sludge's rheological properties measured as viscosity, and its capability to separate from water, measured as capillary suction time. The capillary suction time relationship states that at higher temperature values, the CST is higher, meaning that the water separates from the sludge at a much lower pace, and at lower temperatures the CST values are lower. Lower temperatures could not be tested since the sludge's cooling pace is very slow and it was meaningless to keep reducing the sludge's temperature since the plant's equipment was not appropriate for this purpose.

Although the CST values are slightly better at lower temperatures, this might not be of great importance in the full scale, but when an eventuality would occur and significantly high temperatures were obtained. That is, under a high temperature event, the dewaterability, mainly chemical dewaterability might be deteriorated. Still, there are some fluctuations between the temperature from the sludge that enters into the filter press, it can vary between 23 to 30 degrees, this may also depend on the season. Further studies should be made considering the actual range of temperature fluctuations and how they affect the mechanical dewatering process. However, from the data presented on Figure 15, it seems that maintaining a constant and lowest sludge temperature may help to improve the dewaterability of sludge.

Further experiments were made for the digested sludge on the rheological and dewaterability parameters with polymer dosage. NALCO polyacrylamide polymer was dosified with a fixed dosage of 36 mL for 500 mL of a mixed sample of digester 1 and digester 2. This dosage was taken form the full scale value used at the time with a relationship of 1 m^3 of polymer (with 1% concentration) for a volume of 16 m^3 of sludge. The results from this experiment are shown on Figure 16.

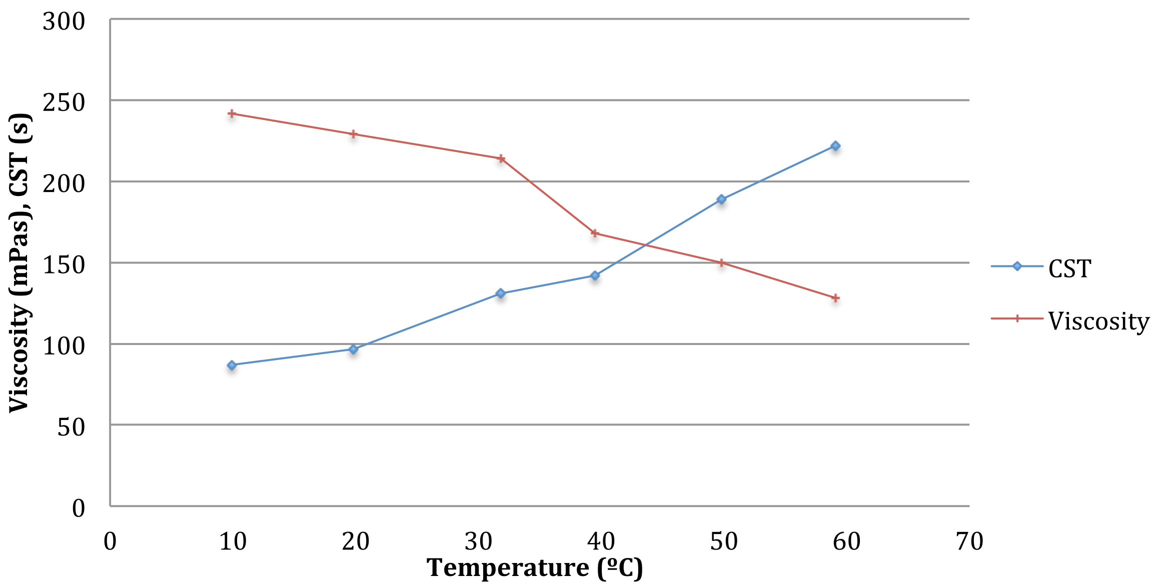

Figure 16. Relationship between T and CST and Viscosity with polymer dosage.

Table 9. Data corresponding to Figure 16.

Temperature (ºC)	9.9	19.8	31.8	39.5	49.8	59.1
CST (s)	87	96.8	130.9	142.1	188.8	222
Viscosity (mPa.s)	241.9	229.1	214	168	150	128.1

From

Table 9, it is observed that CST values were significantly decreased with polymer dosage, although this dosage might not be the optimal, since, according to literature, a CST value of around 10 seconds is necessary in order for the sludge to dewater. Later on, trials were carried out testing different polymer dosage values in order to obtain better CST results.

The sludge's viscosity was also affected by the polymer addition, a less viscous sludge is obtained, and easier to dewater. The flocs were immediately formed after the polymer addition. However the purpose of this experiment was to observe weather the relationship between CST and the other parameters was affected with the addition of polymer.

A similar behavior was observed between the results shown on Figure 15 and Figure 16, nevertheless from this last one, the CST values were lower, and the change with temperature was more linear and smoother than in the latter. The similarity between both figures shows that the behavior between temperature and CST and viscosity is independent from the polymer dosage.

10.1.3. Relationship between polymer dosage and sludge parameters

Samples from the post thickener were taken. The sample was divided in seven samples of 500 ml each. Polymer dosages between 33 and 37 ml were tested on each sample. Viscosity, temperature, pH and capillary suction time were measured according to the analytical procedures described on chapter 9.

Results obtained from this trial are shown on Figure 17. Sludge temperature was also plotted to see weather fluctuations on the results could be also due to temperature, and not only due to polymer dosage.

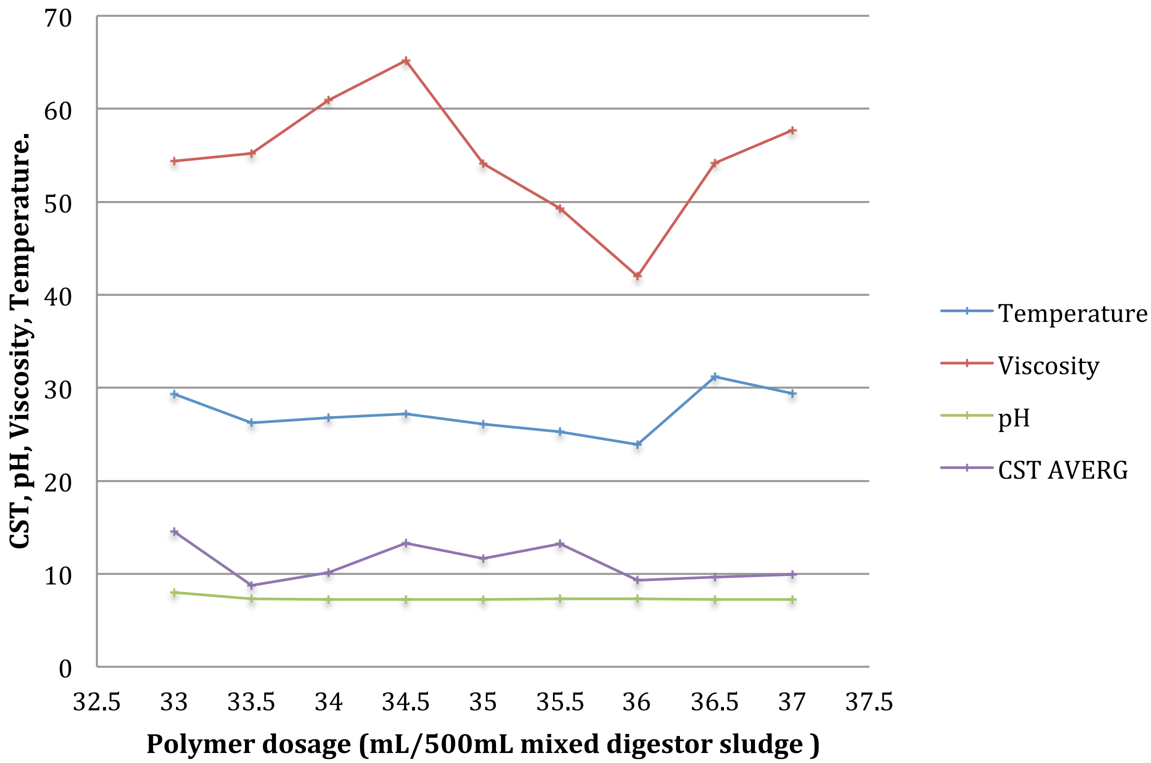

Figure 17. Relationship between polymer dosage and sludge parameters

It was observed that polymer dosage had no effect on pH values. Bigger fluctuations were observed with the sludge's viscosity values, and the polymer dosage had little or no effect on the other parameters. However the best CST results were obtained at polymer dosage values of 33.5 mL and 36 mL per 500 mL of sludge , with CST values of 7.2 and 9.3 respectively. This corresponds to a value of around 1 m^3 per 16 m^3 of sludge that are fed into the filter press each day, wider dosage ranges were later tested on the next subchapter. Also, an important observation can be obtained from previous experiments were only mixed samples from the disgested sludge were taken. On these samples, higher CST values were obtained. As for this experiment, samples from the thickened sludge were used and very low CST values were obtained, this means that good dewaterability properties on the sludge are achieved starting from the thickening process, since samples obtained from post thickener give much better CST results (Figure 17) than the samples taken from the digestion towers (Table 9).

10.2 Polymer dosage optimization

The first polymer dosing test was done with the polymer currently used by the plant as dewatering aid, NALCO ® in 1% concentration. Seven samples of 100 mL of digested sludge were taken from digester 1. Doses of 0, 3, 4, 5, 6, 7, and 8 mL of the polymer were added to each flask and were immediately mixed with a magnetic mixer for 10 seconds, and the capillary suction time (CST) was measured according to subchapter 9.3. Results from this trial are shown on Figure 18.

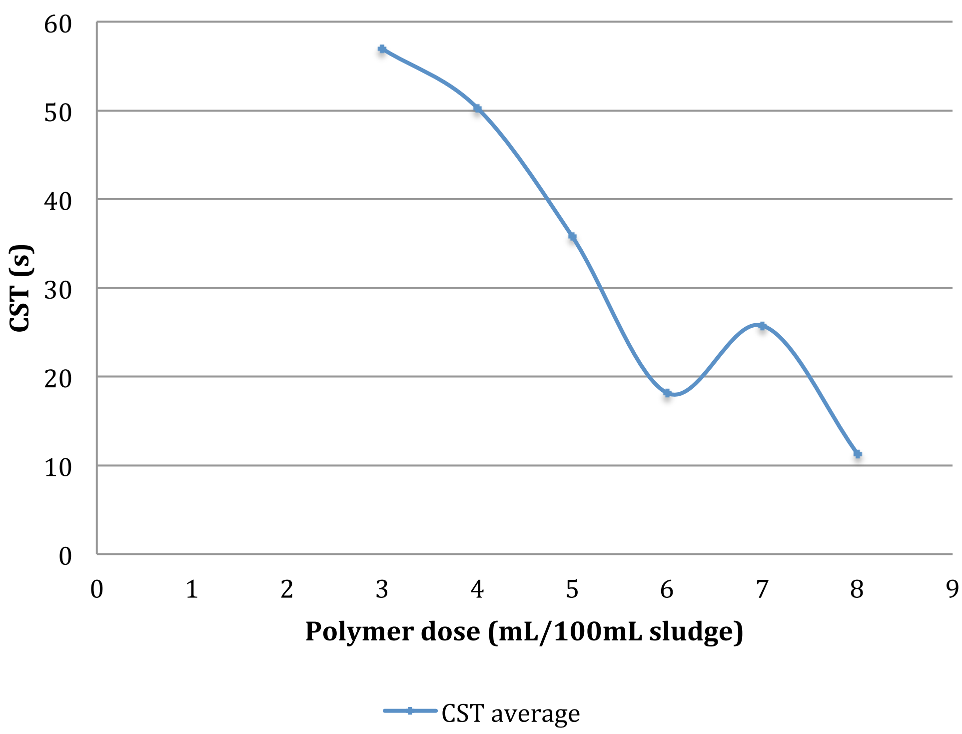

Figure 18. Polymer dosage and CST relationship

Table 10. Data corresponding to Figure 17

Per 100mL							
Polymer dose 1% V/V mL	0	3	4	5	6	7	8
CST average	130	56.95	50.3	35.8	18.15	25.75	11.3

From the previous plot, it is observed that at polymer dosages below five mL, give poor CST results, between 56 to 30 seconds. In the range of dosage from 6 to 8, the CST results were improved (18 and 11 seconds respectively). Therefore, another test was carried using only this last range. For these tests, a digested sludge sample and a thickened sludge sample were used. It is important to remark that sludge coming from the post thickener already has polymer on its composition. The texture is very different from that of the digested sludge, some flocs could be already observed from this sample and also a slight separation of water could be observed. The results from this trial are presented on Figure 19.

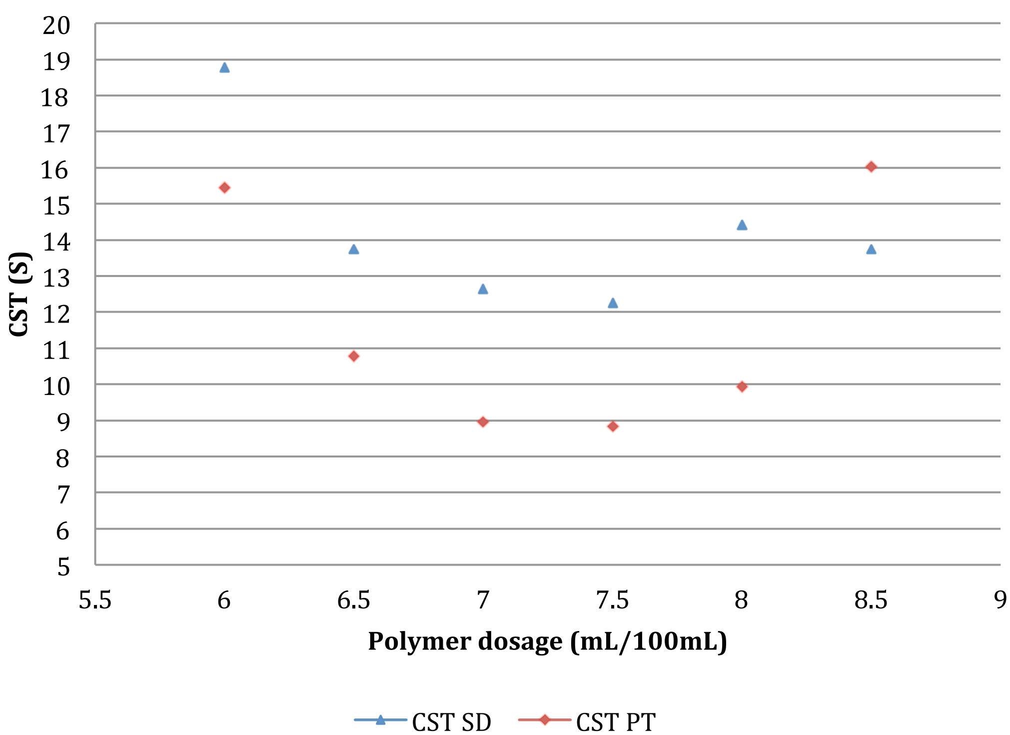

Figure 19. Optimal polymer dosage

From the plot above, the red dots represent results from the post thickener sample (PT), and the blue dots represent the sample from the digester (SD). Both samples followed the same behavior, however, slightly better results were obtained from the post thickener, the dewaterability was in average 3 seconds faster than those of the digested sludge. This shows that the thickening process has a positive effect on the sludge's water separation Also this sludge had improved dewaterability due to the previous addition of polymer. The best CST result was obtained at a polymer dosage of 7.5 mL per 100 mL of thickened sludge, with a CST value of 8.8 seconds. The extreme values of 6 and 8.5 showed higher CST values of 15 and 16 seconds for thickened sludge.

A last trial was carried for the sludge dosage optimization, this time using a bigger sample. A 3 liter mixed sample from digestor 1 and 2 was taken. Then, this sample was distributed in six smaller samples of 500 mL each were polymer dose of 25.5, 30, 32.5, 35, 37.5, and 40, were tested (corresponding to the dosage of 5, 6, 6.5, 7, 7.5 and 8 mL per 100 mL of digested sludge). CST, temperature and viscosity were measured and related to the polymer dosage, pH was no longer measured since it was observed from Figure 17 polymer dosage has no effect on pH, neither does this have effect over the other parameters.

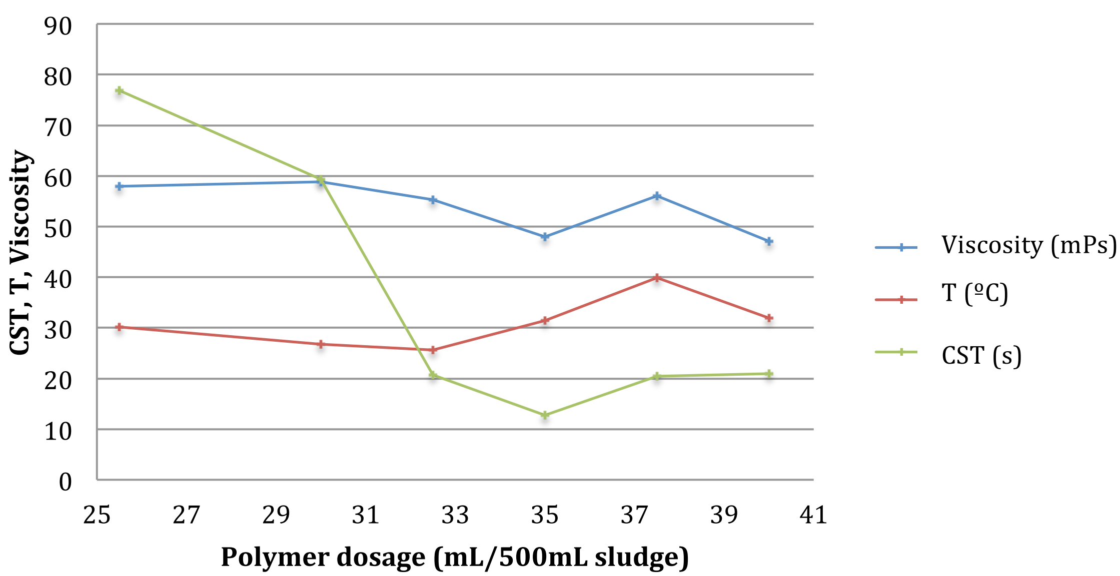

Figure 20. Relationship between polymer dosage and sludge parameters

Table 11. Data corresponding to Figure 20.

Per 500 mL						
Polymer dose !% v/v (mL)	25.5	30	32.5	35	37.5	40
Viscosity (mPs)	58	58.8	55.3	48	56	47.1
Temperature (ºC)	30.2	26.7	25.6	31.4	39.9	31.9
CST (s)	76.9	59.3	20.7	12.7	20.5	20.9

From the previous plot, the blue line represents viscosity, the red temperature and the green one CST, it is observed that the best polymer dosage obtained from this trial was of 35 mL per 500 mL of sludge, this corresponds to a value of 1,12 m^3 per 16 m^3 of sludge in full scale. This is actually the current polymer configuration that is used at Bensberg. However, chemical dosages should be periodically evaluated because of changes in sludge characteristics, also a line CST sensor would be required so when sludge CST values are high, then polymer dosage can be automatically adjusted.

10.3. Kemicond Tests

The Kemicond test can be used prior to dewatering digested or undigested sludge. It operates at low pH values and consists of several steps. In the first step, an anti foam is used to prevent the development of excessive lather, then sulphuric acid (H_2SO_4) is added until a pH value as low as 4. Then a release of gases, mainly carbon dioxide CO_2 and some hydrogen sulphide H_2S occurs. Furthermore, "gel-like water-holding inorganic matter is dissolved and chemically bounded water that cannot be removed with only mechanical dewatering is released, i.e. the iron or aluminium. based coagulants, hydroxides and phosphates are dissolved at this pH, and most of them remain in solution. Part of the organic matter is also dissolved". (Nikolic, Aleksandra; Karlsson, Ingemar, Kemira, 2005, pg.4).

The second step is the addition of a strong oxidizing agent such as hydrogen peroxide to oxidize dissolved ferrous iron, Fe_2^+, to ferric iron, Fe_3^+. Then ferric phosphate and hydroxide are precipitated. pH values decrease and Al continues to dissolve. Furthermore, the structure of the sludge is changed, with the crystalline structure prevailing over the gel-like one, which improves filterability. Hydrogen peroxide oxidize also sulphides, mercaptans, amines and aldehydes produced under biological activity, which reduce sludge odour. Hydrogen peroxide has also a disinfection effect due to additional oxygen source that reinforce the biological treatment, destroying most of the organic traces and pathogenic elements present in the sludge. The contact time for the first two steps is 40 minutes up to one hour. (Nikolic, Aleksandra; Karlsson, Ingemar, Kemira, 2005, pg.4).

The last step prior to polymer dosing is a neutralization with an alkali such as NaOH, in order to increase pH to the polymer's operating values. The final dewatering is done by mechanical means, with screw presses, the sludge can be dewatered with conventional dewatering devices like centrifuges, belt filter presses or chamber filter presses.

Some experiments using the Kemicond procedure were carried out to test the improvement on the dewaterability of the sludge.

Samples of 500 mL of digested sludge were taken. The pH of the sludge was measured. Then, it was transferred to a 600 mL flask and stirred with a magnetic mixer. Five to ten drops of anti foamer were added to the sludge to prevent foam formation after adding sulphuric acid. Sulphuric acid (H_2SO_4) was added with a titer until the pH was lowered to a value of 5 (Figure 21). Then the sludge was divided into five smaller samples of 100 mL and concentrations from 1 to 5 mL of hydrogen peroxide (H_2O_2) were distributed among the samples and it was stirred. The reaction took place in 45 minutes.

Figure 21. Kemicond test

After the sludge was treated, its dewaterability capabilities were tested on an Erlenmeyer vacuum flask (Figure 22). The filter paper was placed at the top of the flask and sludge was poured until the filter paper was fully covered, the sludge was dewatered through vacuum from 1 to 5 minutes, depending on the sample and on its dewatering capabilities. Then the sludge's dried solids were measured according to subchapter 9.1.

Figure 22. Sludge vacuum dewatering to test performance of the Kemicond treatment.

Results from these trials are shown and discussed below.

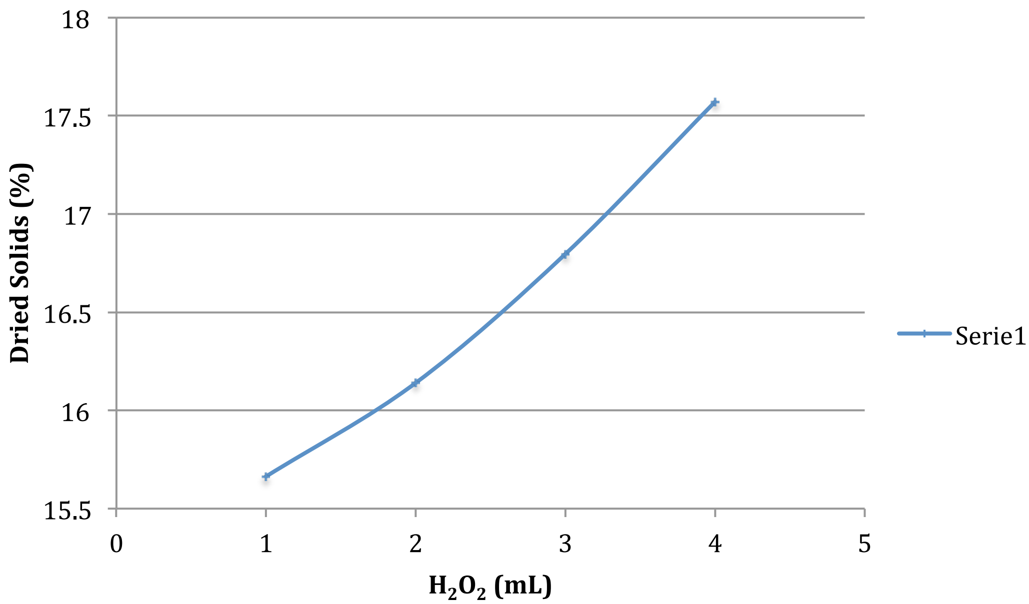

Figure 23. Dried solids percentage for sludge treated with KEMICOND pH =4

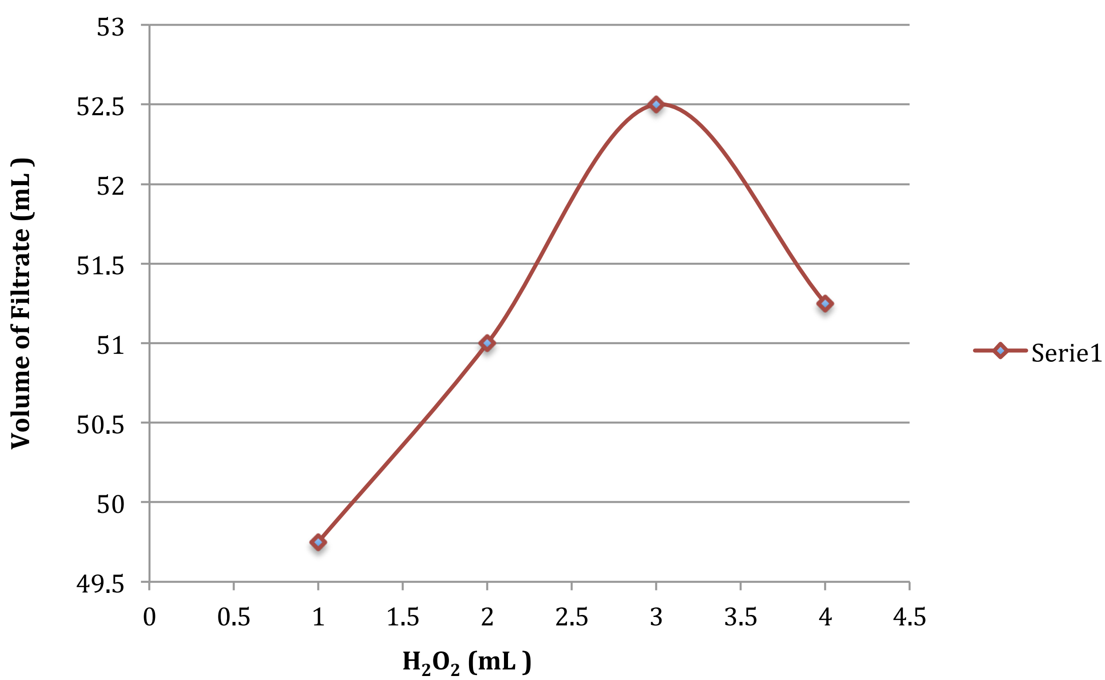

Figure 24. Volume of filtrate of sludge treated with Kemicod, pH=4, at different H2O2 dosages

Table 12. KEMICOND trials for treatment with H_2SO_4 pH=4

H_2O_2 (mL)	Trial	pH	Sludge volume (g)	Dried Solids	Average	Filtrate	Average
1	1	4.03	6.818	16.53	15.66	50	49.75
	2	5.01	7.2	15.85		51	
	3	5.99	7.697	14.64		48	
	4	7	7.119	15.63		50	
2	5	4.01	6.537	15.96	16.14	50	51
	6	5.08	6.614	16.45		52	
	7	6.02	6.809	15.88		51	
	8	6.99	6.671	16.28		51	
3	9	4.03	6.257	17.44	16.80	54	52.5
	10	5	6.334	15.90		51	
	11	5.95	6.198	15.92		52	
	12	6.98	5.69	17.93		53	
4	13	4.01	5.8139	17.06	17.57	49	51.25
	14	4.98	5.806	17.10		52	
	15	5.96	5.6	18.39		53	
	16	6.99	5.805	17.73		51	

After the pH was lowered with sulphuric acid (H_2SO_4), different dosages from hydrogen peroxide (H_2O_2) were tested. Figure 23, shows that the percentage of dried solids is directly dependent on the hydrogen peroxide added to the sludge. A dried solid concentration as high as 17.57 % was achieved with this treatment alone (pH=4 and 4mL of H_2O_2) (Table 12), using only digested sludge, without post thickening or any polymer addition. The vacuum dewatering might not be as effective as the mechanical dewatering used in full scale, therefore the results obtained through this trials are not comparable with press filter dried solids results. It only shows that the dewaterability can be significantly increased with this method, however it could be improved with a polymer conditioning step.

Additionally to dried solids measurement, the volume of filtrate was also measured. Once the digested sludge was placed on the Erlenmeyer vacuum filter, the sludge was left to dewater for 5 minutes, and after this time, the volume was measured. Figure 24, shows the filtrate results, and it can be observed that the filtration volume was also affected by the addition of higher concentrations of H_2O_2. With concentrations between 2 and 4mL the filtration was very quick, within less than one minute the sludge was completely dewatered. The highest filtrate was obtained with an addition of 3 mL of H_2O_2 with a filtrate volume of 52.5 mL.

Unfortunately very few trials were tested with this procedures at a really small range of H_2O_2 addition and only testing for one initial value of pH of 4. After the acid treatment, pH was raised with the addition of NaOH, and pH near 4, 5, 6 and 7 were tested for the different H_2O_2 concentrations (Table 12). However, there was not a clear relationship between the pH value and the dried solids percentage. This may indicate that the NaOH treatment could serve only to produce a less acid sludge, but it does not affect its dewatering capability.

This sludge conditioning; however, might require special equipment since it is very aggressive. Also large quantities of sulfuric acid and hydrogen peroxide would be required for the amount of sludge treated. An average of 50 L of H_2SO_4 and 30 L of H_2O_2 would be required per 1 m^3 of digested sludge, an average of 112m^3 of sludge is treated per day at the plant. This would represent a need for H_2O_2 of 1200 m^3 per year and 2000 m^3 of H_2SO_4 per year.

CHAPTER 11. PILOT SCALE TRIAL

A small scale filter press was reactivated from Senger, 2008, it consists on a circular platform, with a cylindrical tube (Figure 25) in which a membrane used for the filter press was inserted (Marsyntex®). A sample of 150 mL from the anaerobic digestion outlet was taken (without polymer), and another sample from the inlet to the filter press was taken (sludge with polymer). The sludge was placed on the cylindrical tube. Then, a piston was introduced into the cylindrical cavity and was pressed with a 500 kg pump to produce a pressure similar to that of the filter press (Figure 26). On the bottom a small bucket was placed to collect the filtrated water.

Figure 25 . Filter press piston

Figure 26. Application of heavy weight-

Experiments were ran for 60, 90 and 120 minutes. After that, a thin sludge cake mass was obtained (Figure 27) and the total solids were measured.

Figure 27. Sludge cake obtained from small press

Results obtained from this pilot scale study were inconsistent; the dried solids content could not be comparable to the full-scale results. Also, old material was used for the construction or reactivation of the small press and it was not completely sealed; sometimes the pressure was not evenly distributed so a great variability of dried solid results was observed from one test to another. Sometimes the dried cake was very well pressed and dewatered, and others it still had a high water content, and the cake was very soft, giving poor DS results. Also a great amount of time was spent (60-120 minutes) to obtain a single result.

Nevertheless, a new pilot scale filter press was constructed and tested by Kowalski (2011) at Bensberg WWTP, the design was retrieved from the University of Damstadt in Germany, this press intends to be useful for pilot scale studies.

It is based in a very simple mechanism of compression. The base of the press has several small perforations in order to allow the water to flow out of the sludge (Figure 28). The filter membrane is located on top of the base. Then the hollow cylinder is placed and perfectly attached with screws to the base to prevent the sludge from falling to the sides, then the cylinder is filled with the conditioned sludge and it is pressed with a cylindrical piston with additional pressure.

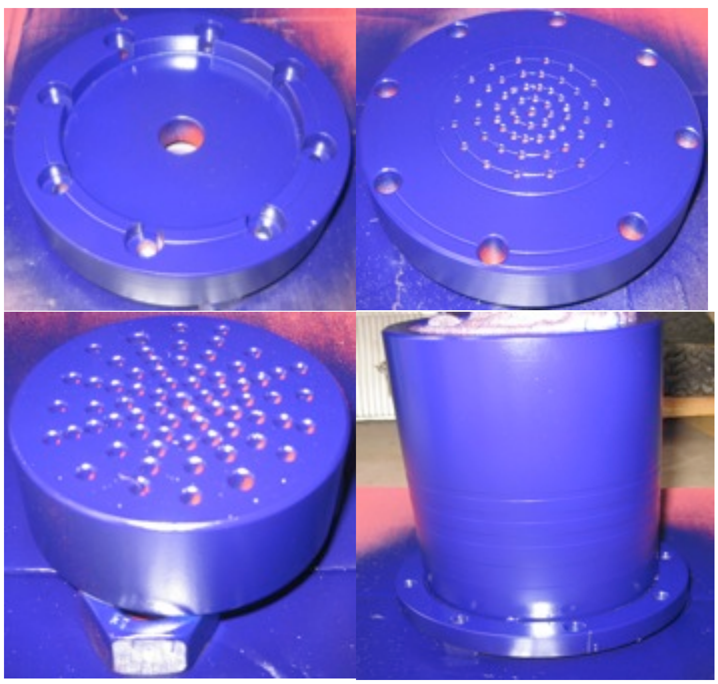

Figure 28. Pilot scale press.

Some trials were carried with this press, first raising the pressure up to 62,5 bar for five minutes, and the pressure was held for 15 minutes, then, Kowalski used a pressure of 12,5 bar and left the pressure for 30 minutes. With this last trial he obtained very precise results in comparison with the full scale (a dried solid content of 26% for each press).

After the small scale, and pilot scale trials, full scale trials were conducted in the plant's filter press (Figure 29), were the best addition point for the conditioner, dewatering time, and total solids content were studied. Also the plant's personnel installed a new mixing pump, and membrane filters, and dried solids were measured with these process modifications.

Figure 29. Filter press in Beningsfeld WWTP

12.1. Filter press performance.

The performance from the filter press was tested measuring the filtered cake dried solids content. Many factors can affect the press' performance. One of these factors is the filter membrane material used; at the time of the sampling there were different types of membranes placed in a single press. Another factor is the pressure; at different points of the press, different pressures might be achieved, and also pressure can be variable within the length of the press. Another factor is the distribution of the sludge in the height of the filter membrane, the further away the sludge is from the distribution entrance, it is possible for it to be drier.   Therefore, it was important to take the samples in different parts of the press.

Samples were taken from 3 different points from each press. There are two filter presses operating in Bergisch Gladbach WWTP, each press consists of 72 plates. Therefore, samples, were taken at the beginning of the press (plate number12), at the middle of the press (plate number 34) and at the end of it (plate number 62). Also, for each plate, three samples were taken, above, below and middle of the plate, (Figure 30), adding up to a total of nine samples per press (Figure 31). This procedure was repeated through 14 days.

Figure 30. Filter press sampling at nine different points.

Figure 31. Samples from one filter press.

Results obtained from these series of trials are shown on Figure 32 and on Table 13 for filter press 1, and on Figure 33 and Table 14, for filter press 2.

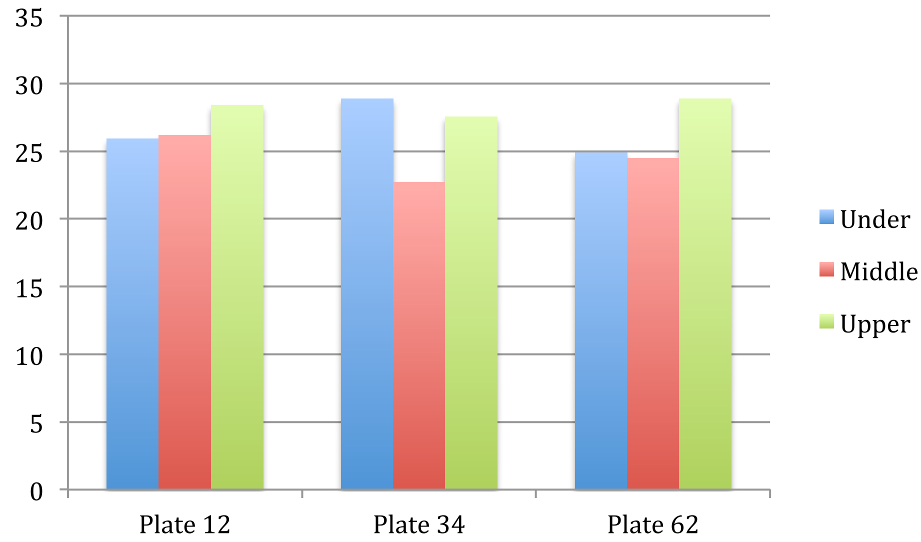

Figure 32. Percentage of dried solids on filter press 1.

Table 13. Average dried solids content for filter press 1.

%Total Solids Press 1				
	Under	Middle	Upper	Average
Plate 12	25.91	26.18	28.38	26.82
Plate 34	28.88	22.70	27.55	26.38
Plate 62	24.90	24.47	28.86	26.08
Average	26.56	24.45	28.26	

From the plot on Figure 32 a higher solid concentration is observed in the upper part of the plate (28.46%), were lower dried solids are achieved from samples taken from the middle part of it (24.45%). DS values are very similar along the length of the filter press, achieving the lowest DS for plate 62 with 26.08% and the highest DS was achieved on Plate 12 with 26.82%. Also, on the first and last monitored plates (Plate 12 and Plate 62) very similar dried solids results were observed for the upper part of the plate (28.38% and 28.86% respectively). Whereas very poor DS were obtained at the middle part of the press on plate 34 from the middle sample. However, in average, the distribution of DS is even or less homogeneous along the filter press.

The results from filter press 2 are displayed in the following plot and table.

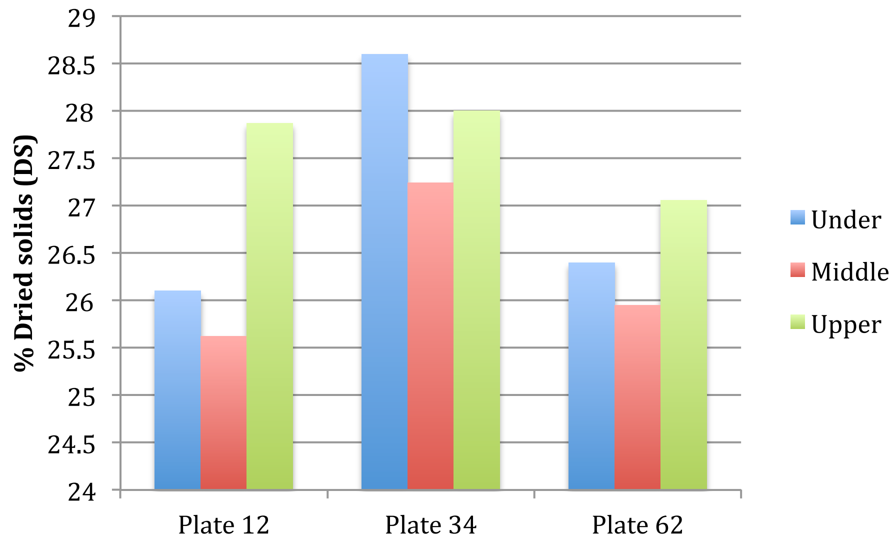

Figure 33. Percentage of dried solids from filter press 2.

Table 14. Average dried solids content for filter press 2.

%Dried Solids Pres 2				
	Under	Middle	Upper	**Average**
Plate 12	26.10	25.62	27.87	26.53
Plate 34	28.60	27.24	28.00	27.95
Plate 62	26.40	25.95	27.06	26.47
Average	27.03	26.27	27.64	

For performance of filter press 2, there is a more noticeable difference than on filter press 1 considering the length of the press. The behavior from both presses is not very different, since they are fed with the same sludge. Other parameters might influence their behavior, such as the membranes usage, and other hydraulic parameters that will be later analyzed.

Another trial was carried taking a larger sample from the filter press of approximately 50 cm x 20 cm, samples were taken from the same spots as the previous trials, this larger sample was pulverized and a mixed for the dried solids measurement. This was done with the objective of having more reliable results from the filter press performance, since in the previous tests very small samples were taken. Average results from this trials are shown below.

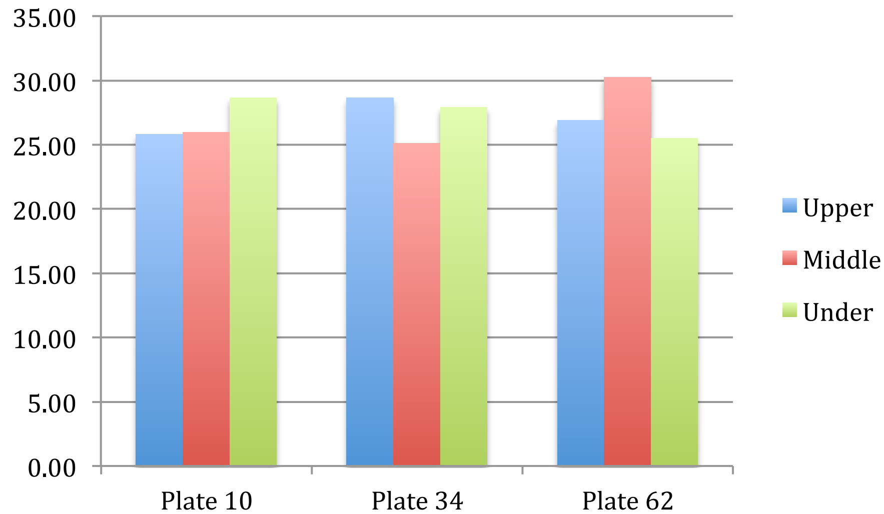

Figure 34. Dried solids filter press 1 with larger sample

Table 15. Dried solids filter press 1 with larger sample

	Plate number			Average
	P10	**P34**	**P62**	
Upper	25.82	28.66	26.92	27.13
Middle	25.95	25.12	30.24	27.10
Under	28.64	27.91	25.52	27.36
Average	26.80	27.23	25.52	26.52

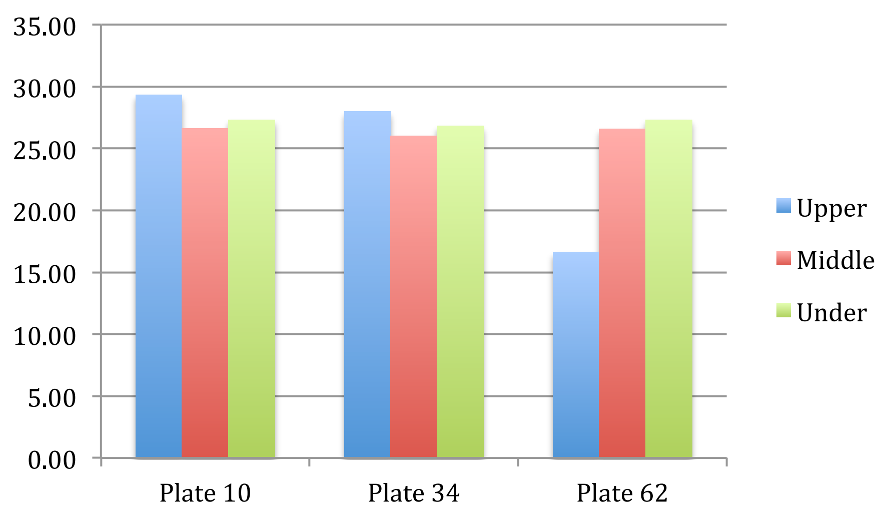

Figure 35. Dried Solids from filter press 2 with larger sample.

It is observed that when bigger samples are taken, there are smaller differences between the dried solids results at different spots. Therefore, it is better to take a mixed sample for more reliable total solids analysis. The dried solids values are similar between the different points of the filter press, and this type of sampling is more reliable than the first one were bigger fluctuations are observed from one point of the press to another, and from different points within the plate.

The plot below shows the total solids content for a one-month period. There are significant fluctuations between the values from one date to another. This might mean that the sludge quality is variable from one day to the other. Sludge fed into the press comes from the post thickening process in which some polymer has already been added. However, sometimes a poor mixture of polymer occurred in this process since sludge is continuously fed into the filter press and there is not enough time for it to be homogeneously mixed with chemicals. This might also have a negative impact on the final dried solids results. Even though, the same sludge is fed into both presses there is a slight difference between the performance from Filter Press 1 and Filter Press 2. Filter press 2 has better dried solids results. Additionally, this press was easier to handle in comparison to press 1. The filtered cake was easier to detach from the filter membrane, and a more compact cake was obtained. Filter press 1 was very difficult to handle, the filtered cake was strongly attached to the membrane, and more time was spent by opperators to clean the press. Also a thicker cake was formed, and the dried solid content was regularly lower than that on filter press 2.

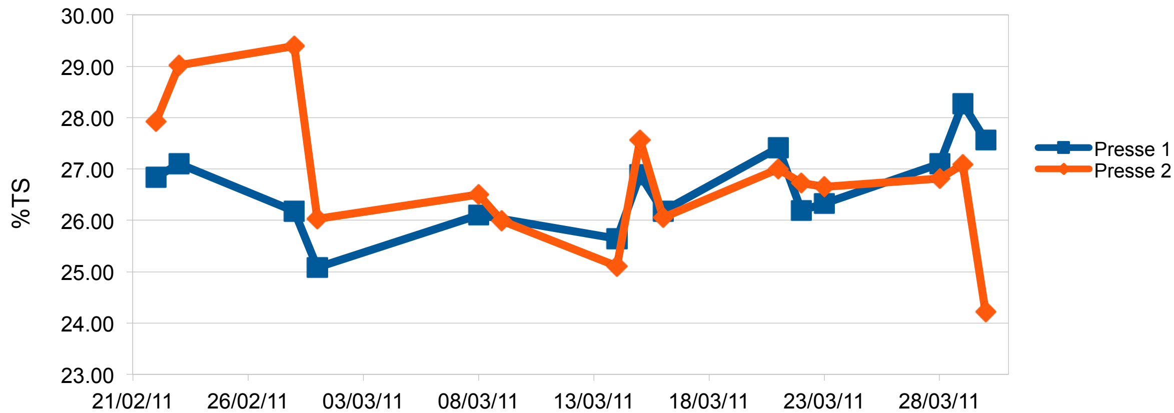

Figure 36. Dried solids Press 1 and Press 2.

12.3. Filter membranes.

The filter membranes might be wore out throughout the usage. Therefore it is important to replace them every 3 to five years for a better performance on filter press dewatering.

All of the previous full scale trials were done with old membranes from three different providers. However, Beningsfeld WWTP recently replaced the old filter membranes (mainly Marsyntex ®) for new ones, (Clear Edge ® on filter press 1 and Sefar ® on filter press 2). Technical data from the different membranes is shown on Table 16.

Table 16. Filter membranes' technical data.

Membrane	Material	Weight (g/m^2)	Thickness (μm)	Permeability $L/dm^2/min/200Pa$
Marsyntex®	Monofilament	285	420	300
Clear Edge®	Polyamide Monofilament	350	530	400
Sefar®	PP Monofilament	250	390	156

Although polymer monofilament is a common material between all of the membranes, they have very different weight, thickness and permeability specifications that may differentiate their performance. Further dried solid tests were made testing the performance of these new membranes. The tests were carried mainly on Filter press 1(with Clear Edge ® membrane). Data from these trials is shown on subchapter 13.4 among with other hydraulic parameters.

Some of the advantages that were immediately observed after the membranes were changed are the following:

- The filtered cake was easily detached.
- There was a more uniform elutriation on the entire filter cake.
- Less time spent emptying the filter press after each cycle.
- Less sludge residue was observed on the membrane.

Figure 37 through Figure 39 show a microscopic picture of filter membranes.

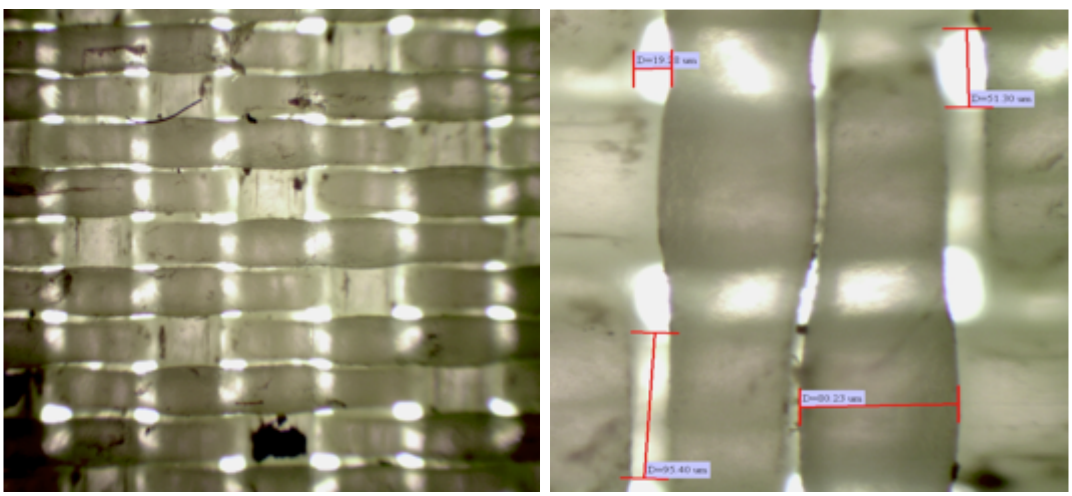

Figure 37. Marsyntex filter membrane.

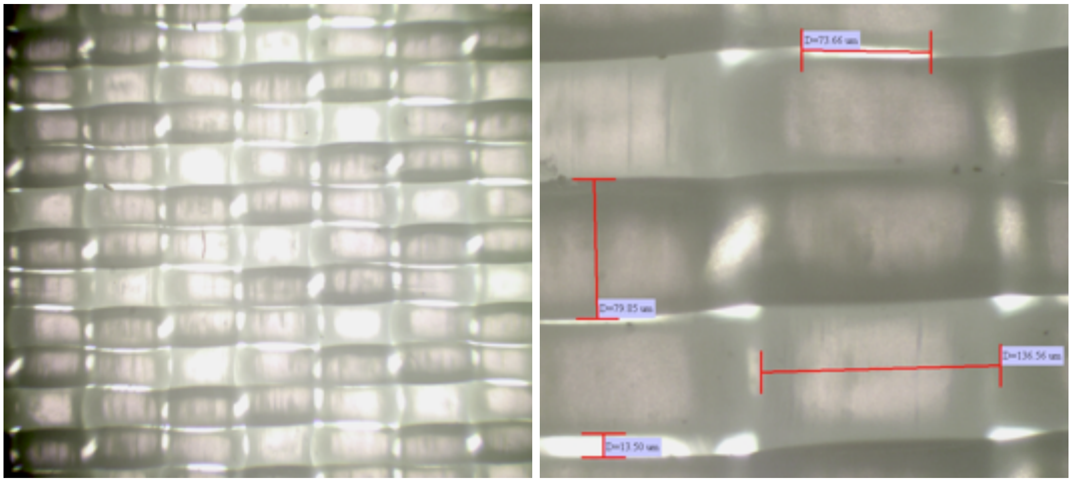
Figure 38. Clear Edge filter membrane.

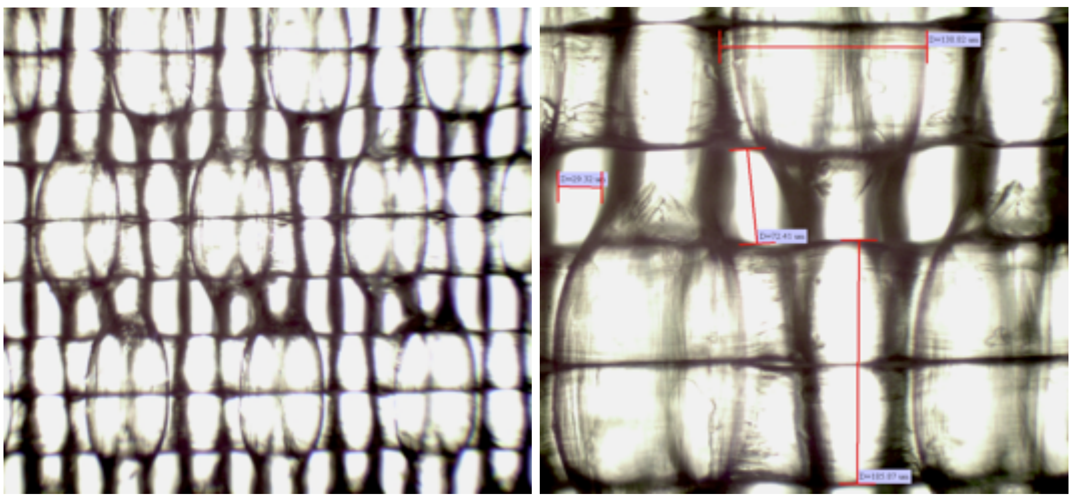
Figure 39. Sefar filter membrane.

The first one, Figure 37 a Marsyntex® filter membrane is shown, this is actually an old membrane, there are still sludge fragments strongly attached to the filaments of the membrane, this might have led to some clogging and the already mentioned operational difficulties since hard scrapping was required to remove or detach the cake from the membrane. The differences on the weave structure can also be observed from the pictures above. Sefar membrane (Figure 39) has a tighter weave than the first two membranes. This corresponds to its lower permeability- Although the cake was very easily detached from the membrane, thinner cakes were obtained from this type of membrane. In general, high benefits were obtained in the operational level with the replacement of the membranes. However, this was not necessarily reflected on the dried solids content which will be discussed on the next subchapter.

12.4. Modification of Hydraulic Parameters

The total time for the dewatering process is 120 minutes, within this time, there are several steps involved. First, the filling of the press, then the pressure is raised up to 15 bars, afterwards, compression takes place, and lastly the sludge goes through a hydraulic compression. Normally the press operates with 300 seconds of filling and 2400 seconds of compression. The dried solids analysis was done with these parameters for press 1 were the new Clear Edge@ membranes were tested. Samples were taken from plate 12, 24 and 62, they were shredded and mixed; dried solids were analyzed from the mixed sample according to subchapter 9.1.

Also, dried solids from the inflow are measured through a radiometric sensor; this value was registered for each cycle. The radiometric dried solids value was compared to the value obtained from the analytical dried solids measurement. This was achieved by taking the sample within one minute exactly from the sludge inlet previous to polymer dosage, and the radiometric measurement was registered at the same time of the sampling. The influence of the dried solids content on the final sludge results was analyzed. Also, the polymer addition was registered. Results obtained from this trial are shown on Table 17.

Table 17. Trials for Filter press 1 testing 300 s of filling and 2400 s of hydraulic press.

Inlet DS Load (%)	Inlet DS (%)	Cake dried solids (%)	Dosage of active subtance kg AD /kgDS
4.11	4.5	24.79	5.0
4.30	4.0	24.09	6.0
3.55	3.5	24.75	6.0
3.81	3.8	23.37	6.0
3.67	3.5	22.95	6.0
3.89	3.8	26.07	7.5
3.75	3.60	25.10	7.5
3.87	**3.81**	**24.45**	**6.29**

From the table above, it is clearly observed that the dried solids content was deteriorated with the implementation of the new filter membranes (Clear Edge®), its characteristics are shown on Table 16. Although the removal of the dried cake from the sludge was much easier, a poor solids concentration was obtained and the texture of the cake was soft and humid. These results were obtained within the first days in which the membranes were implemented, therefore they might need an adaptation period for the dried solid results to be improved.

Also, different dosages were tested from 6 to 9 kg/DS. The dried solids were improved at dosages around 9 kg/DS. There is also not a clear relationship between the dried solids of the inlet and the solids concentration from the dried cake.

The following measurements were made rising the sludge filling time from 300 to 600 seconds and lowering the post pressing time from 2600 to 2100 seconds. The dosage was fixed at 8 kg/DS. Additionally, viscosity and temperature were measured according to procedures described on subchapter 9.2.

Table 18. Trials for filter press 1 with 600 seconds of filling and 2100 seconds for post pressing.

Inlet DS Load (%)	Inlet DS (%)	Cake dried solids (%)	Dosage of active subtance kg AS/kgDS	Viscosity (centipoise cP)	Temperature (ºC)
3.80		23.30	8.0		
3.55	3.25	26.73	8.0		
3.57		26.24	8.0		
3.29	2.99	26.30	8.0	151	26.2
3.52	3.75	27.90	8.0	244	30.1
3.54	**3.33**	**26.09**	**8**	**197.5**	**28.15**

From the table above, an improvement on the dried solids concentration was observed in comparison with the first measurements. Therefore, the filling time may have a big influence on the overall filter press performance, it is also possible to reduce the post pressing time, this process does not have a big influence on the dried solids concentration, it also demands a big amount of energy, therefore, reduction on the time of the post pressing may be desirable for energy saving. Viscosity and temperature was also variable, although further viscosity measurements were made on the next trials to see the relationship between viscosity and dried solids.

A last trial was done with a further increase on the filling time, from 600 to 900 seconds and post pressure was decreased from 2100 to 1800 seconds. Polymer dosage was also left constant on 8 kg/ DS and it was modified only for the last two trials, were it was decreased by 0,5 kilograms. Viscosity and Temperature were also registered.

Table 19. Trials on filter press 1 with filling time of 900 seconds, and post pressure of 1800 seconds

Inlet DS Load (%)	Inlet DS (%)	Cake dried solids (%)	Dosage of active subtance kg AS/kgDS	Viscosity	Temperature
3.49	3.66	27.00	8.0	219	29.9
3.34	3.61	26.90	8.0	206	30.6
3.31	3.34	25.75	8.0	177	30.6
3.36	3.35	24.97	8.0	187.8	29.9
3.54	4.07	26.25	8.0	258.1	24.5
3.64	3.84	27.05	7.5	205.7	24.8
3.65	3.44	27.41	7.5	218.5	24.7
3.45	**3.62**	**26.57**	**7.88**	**210.3**	**27.86**

From Table 19 an improvement on the dried solids content was also observed, compared to previous trials. On this trials the polymer dosage was kept constant. It seems that the filling time is an important parameter because a slight improvement was observed when modifying this parameter. The post-pressing time did not have a significant influence on the final dried solid results. Therefore this time can be decreased.

The statistical correlation between cake dried solids and viscosity is very low, of 0.4. Furthermore, a higher statistical correlation was observed between cake dried solids and inlet dried solids, of 0.84. The solids concentration in the inlet sludge is dependent upon the thickening process, therefore, when a successful thickening is obtained this may improve the cake dried solids concentration.

The next table shows results with the installation of a dynamic mixer previous to the press filling.

Figure 40. Dynamic mixer

Table 20. Trials proving the installation of a dynamic mixer previous to filter press filling.

Inlet DS Load (%)	Inlet DS (%)	Cake dried solids	Dosage of active subtance kg HW/TR	Viscosity	Temperature
3.29	3.3	25.58	9.0	324	27.6
3.34	3.8	24.39	8.5	308.4	30.4
4.16	4.1	24.22	8.0	313	30.6
4.27	4.1	25.97	7.5	304	30.8
4.36		26.77	7.5		
4.36	4.6	27.90	8.5	341.5	29.9
3.78	3.4	30.26	7.5	310.8	29.9
3.53	4.2	25.63	7.5		
4.22	4.4	26.53	8.5	324.8	26.3
3.96	4.1	22.94	7.5	380.2	25.9
4.48	4.6	25.16	8.0	324	30.9
4.33	4.2	26.07	8.0	308.4	27.6
	4.1	27.9	8.0	320	30.4
	4.1	28.06	8.0	209	31.4
4.01	**4.07**	**25.95**	**8**	**323.91**	**28.99**

Several measurements were done with the installation of the dynamic mixer, however, no improvement on the dried solids content was observed, having an average dried solids content of 25.95%, in comparison with the dried solids obtained without the dynamic mixer of 26.57%. This might be due to the location of the mixer, which is right before he sludge enters the press, other locations should be tested, for instance, after the polymer addition, or in the thickening process, to have a better distribution of the polymer added to the sludge.

Also, some dried solid measurements were done on Filter press 2 were the old membranes were replaced with Sefar membranes, a total of five mixed samples were taken, having an average dried solids yield of 26.75, achieving a yield as high as 28.23% and 25.35 % was the lowest yield obtained.

CHAPTER 13. CONCLUSIONS AND FURTHER IMPROVEMENTS

The main conclusions that can be drawn from the experiments are that the dried solids content could not be improved in the full scale. However, some parameters were found to be of importance for the dewatering improvement.

Polymer dosage at small and large scale

Although the best polymer dosage tested in a lab scale with better CST results was on the range of 7.5 to 8.5mL of NALCO polyacrylamide polymer per 100 mL of digested and thickened sludge, once this range was tested on the full scale, there was not a representative difference observed on the dried solids results. Therefore, the polymer dosage tested in the small scale cannot be interpolated to the full scale, or a wider range should be tested in order to see a difference when higher volumes of sludge are being conditioned. In general, the polymer dosage that was used at the plant, was the right dosage, and higher or lower dosages did not have influence on improving the dried solids content.

Filter press sampling

For the first filter press sampling a very small area at each plate was taken. However larger samples should be taken and mixed to have better results. The plants' laboratory tests include the measurement of the filtered cake total solids from Filter Press 1 and 2, which is usually done twice a week. However, the sample is taken at a single point of the press, and the sampled plate is always different. This kind of sampling might not give reliable results so a larger and more thoroughly sampling procedure should be requested by the laboratory assistant in order to have an effective monitoring of dewaterability yields since in practice it was observed that sometimes there could be great variability on the sludge's dried solids results not only between one plate and another but within the plate itself, so this could be taken into account to improve analytical procedures in the facility.

Trials with different polymers

Unfortunately, only one polymer could be tested in the plant, since there was only one provider (NALCO). Dewatering polyacrylamide based polymer from this provider has been widely used at the plant so they are already familiarized with its performance. However, further studies should be carried to test different polymers and prove their dewatering performance to make sure that the best available product is being used. Also, the alternative natural flocculants should be regarded by the plant in the case that the sludge is disposed for agricultural uses. Trials should be carried out to state best natural polymers in case of future restrictions on the disposal of sludge with non-degradable compounds. Although many natural polymers are still being developed and tested, there are chitosan based polymers already available in the market which could be tested by the plant in a small scale, and it can also be incorporated into the water treatment process for flocculation in order to produce more biodegradable sludge, this natural polymers are cheaper than synthetic polymers, iron or aluminum salts, so they could help not only to produce environmentally safe sludge but it could also help save costs on the dewatering and flocculation process since a big part of costs are designated to costly chemicals.

Filter

Although higher dried solids were not achieved with the replacement of old filter membranes with new membranes, there was a considerable improvement observed at the operational level. After the press cycle came to an end, the filtered cake fell directly after the plate was opened, this saved much time and work for the operator since with the older press scrapping was needed to clear the press.

Improvement of the thickening step

This research was mainly focused on the filter press performance, however a great part of the dewatering process starts with the gravity thickening. Here there is also polymer addition. This process is carried out on a circular tank, the polymer is added at the top of the tank and it is slowly mixed. However, the concentrations of polymer are not the same at different levels of the tank and this might also cause great variability between the compositions of the sludge that enters into the filter press. Perhaps a more effective mixing should be tried in this step in order to have an homogeneous mixture of sludge and the polymer, the new dynamic mixer could be also tested in this location. Another possibility is to analyze the construction of an additional storage tank in order to allow the thickener to have enough mixing time before the sludge enters into the filter press

Pilot scale trials implementation

Pilot scale trials could be of great use for the plant since different polymers and different types of filter membranes, among other parameters that wish to be modified, could be tested before scaling up to the full level, saving time and money. This will give closer results than small scale trials such as capillary suction time testing or specific resistance to filtration, since a pilot filter press is a smaller version of what is intended on the full scale filter press.

Despite the tests carried by Kowalski, several trials should be made in order to compare the results obtained from this press and the full-scale press to test its reliability, and its closeness to the real scale machinery. Once the pilot scale press performance is tested and approved, several small presses can be constructed in order to have pilot scale trials simultaneously with the same sludge and without spending as much time as it would take to dewater in the full scale. It is very important that the plant has its own pilot scale procedures to have an idea of how different parameters will affect the press performance and prevent bigger spillage while trying to optimize the full-scale process.

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