Sludge dewatering with different coagulants

Comparison between sludge from Heerenveen and Garmerwolde

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Abstract

Experiments are done on lab scale with sludge from Garmerwolde and Heerenveen. The goal was to determine important differences between the sludges and coagulants. Garmerwolde sludge had a darker colour than Heerenveen sludge. It was also seen that Heerenveen sludge contained much more pollutions such as twigs and hairs. The odour of Heerenveen sludge was also much stronger. These differences can be explained by the fact that Garmerwolde sludge is digested and the organic material is therefore lower.

An optimum dry solid content for Garmerwolde was not reached yet but with a dosage of 167.5 g/kg sludge DSC, a dry solid content of 30% could be reached. However this dosage is too high to use it in practice. In the case of Heerenveen there was an optimum dry solid content with a dosage of 88.5 g/kg sludge DSC. With this dosage a dry solid content of 27% is obtained.
An improvement of the dry solid content is not acquired with the use of magnesium salts as coagulant. With both sludges it was seen that manually dewatering using a filter, was difficult. There were more flocs formed with $MgCl_2$ but still the water was more unclear than using $FeCl_3$. Probably the settle time needs to be increased if higher dry solid contents should be reached.

Both sludges require a suitable dosage of coagulant and flocculant. Wrong amounts of coagulant and flocculant cause too large flocs. When the flocs are too thick, the sludge cake will be thicker as well because dewatering is difficult and the filtration resistance will increase.
When the dosage of coagulant and flocculant is too low, it is not possible to obtain a sludge cake at all because of the absence of flocs.

Preface

This report is the final result of my bachelor graduation project. In this project several aspects of my bachelor curriculum at the University of Groningen come together. The subject of this research, 'Sludge dewatering using different coagulants', has a large part of experimental work, 200 hours. The lab work couldn't be finished within three months if I didn't have an effective collaboration with Henrieke Heideman. We kept each other focused and had many discussions about a good implementation of the experiments. Without her, the experimental days would be much longer and harder, Henrieke thank you for our nice teamwork.

The other part of this research was to process the data to conclusions, assumptions and recommendations. Also in this part I worked together with Henrieke. I also want to thank prof. ir. M.W.M. Boesten for discussing with us and letting us free in which direction we wanted to do experiments. The experimental work couldn't take part if we hadn't the great support of the technical staff from the Chemical Engineering department. Thank you, Marcel and Anne for helping us with the equipment.

Without Sietze Slump, I could have never know so much from the wastewater treatment plant in Heerenveen. He spent a whole morning with Marc Meijerink and me, answering our questions. Everything we wanted to know, he was willing to give us even though he had to look it up somewhere. Without all this information, my research would not be complete. Because I had no knowledge at all about sludge, it was nice to discuss with Marc Meijerink about the sludge dewatering installation in Heerenveen. It helped me a lot to understand the process and prevent fails in the report, thank you for this.

At least I want to thank my parents, who have ensured my persistence during my study. Every time I thought I would never finish this research or I was just too busy, a little voice in my head said: 'Kom op, nog even doorzetten!' Also Victor, who was a great help for me with distance myself from the research which gave me new energy.

List of abbreviations

GW	Garmerwolde
H	Heerenveen
DS	Dry solid
DSC	Dry solid content
PE	Poly electrolyte
rpm	Rotations per minute
wt%	Weight percent
WWTP	Waste Water Treatment Plant
RWZI	Riool Water Zuivering Installatie (Dutch)
SDI	Sludge Dewatering Installation
SOI	Slib Ontwatering Installatie (Dutch)

Experimental coding

201	Experiment 20 batch 1
213	Experiment 21 batch 3
3111	Experiment 31 batch 11

1. Introduction

Sludge from wastewater treatment plants (WWTP) is currently dewatered as much as possible using sieve belt presses, centrifuges or filter presses. In this research there will be focused on sludge dewatering in Heerenveen where filter presses are used. The sludge from Heerenveen will be compared with sludge from Garmerwolde, were the dewatering also is by filter presses.

The dewatered sludge still contains only 20-25% dry solid which means there is still much water. When sludge is pressed using a filter press this results in a sludge cake. The high content of water in sludge cakes is unwanted because this makes it difficult to use sludge cakes as an energy medium and increases the transport costs. Besides this, sludge dewatering is an expensive matter. Therefore it is interesting to increase the dewaterability of sludge.

At the same time there are signals at the WWTP's that the dewaterability of sludge decreases. For example in Heerenveen, they discovered a poor dewaterability of Leeuwarden sludge in comparison to other provided sludges. The reason of the poor dewaterability isn't clear yet. Often this degradation is assigned to the degree of the digestion of the sludge, the kind of dewatering machine and the quality of the type of poly-electrolyte (PE). In Heerenveen there are experiments performed with different PE's but using a different PE couldn't be related to the dewaterability of the sludge from Leeuwarden. At this moment there isn't an analysis available that explains the poor dewaterability of sludge, so experiments are performed for determining the pH and organic material. (J. Nieuwlands, 2011)

Pure sludge has a low dewaterability. In practice, prior to the mechanical dewatering processes, the sludge is flocculated by addition of chemicals. Flocculation occurs when small particles form larger flocs. First a coagulant is added for destabilizing small particles, where after a flocculant is added which will ensure that the flocculation process will start to work.

The objective of this research is to compare the physical characteristics of Heerenveen and Garmerwolde sludge. Comparison between the sludges is also done using different coagulants. In both installations there is used $FeCl_3$ as coagulant. Magnesium salts ($MgCl_2$ and $Mg(OH)_2$) are also tested as coagulants with both sludges. The used flocculant is always the same, the PE that is used in Garmerwolde. The flocculated sludges are pressed using a one chamber press. From the resulting cakes the dry solid content (DSC) is calculated. The height of the DSC's will indicate if the sludge has a high or low dewaterability which corresponds to a good or bad coagulant.

2. Wastewater treatment in Heerenveen

Figure 1 WWTP and SDI (in an orange circle) in Heerenveen [1]

The wastewater treatment plant (WWTP) in Heerenveen and the sludge dewatering installation (SDI) are two independently working installations. The WWTP will be described briefly because the focus in this research is on the SDI. The SDI will be described more extensive using with block diagrams and process flow diagrams.

2.1 Wastewater treatment plant

The average inlet of wastewater is 675 t/h (675 m^3/h). First the wastewater will go through grid filters to remove the coarse dirt from the water. The grid filters have a gap width of 5 mm. The removed dirt is dewatered using presses and subsequently dumped in a container, which will transported to a suitable waste dump. (Wetterskipfryslan)

After passing the grid filters, the wastewater will be divided and entered in the two lanes. Every lane has a selector, an active sludge space and two sedimentation tanks.

Selectors
The two selectors have a capacity of 645 and 880 m^3 respectively and the wastewater will be contacted here with the return sludge (from the sedimentation tank) using intensively stirring. The organic compounds from the wastewater will be incorporated in the sludge flocs resulting in a better settlement of the sludge in the purification step.

Active sludge space
From the selectors the wastewater will enter one of the two active sludge spaces with a capacity of 8750 and 11750 m^3 each. The active sludge space in lane-1 has two point aerators and two propellers. The active sludge space in lane-2 has three point aerators and two propellers. The insertion of oxygen will remove the contamination of bacteria (those will be oxidized). For the purpose of a good nitrogen removal, the two aeration streets are managed that the aerated nitrate-rich sludge is returned back to and mixed with the fresh sewage.

To control the different processes, all five aerators and four propellers are controlled individually by several (intercommunicating) oxygen meters. The residence time of the sewage water in the active sludge spaces is almost two days when the inlet is average. The residence time when the inlet is maximal, for example with heavy rainfall, is 4 hours.

Sedimentation tanks
The purified sludge-water mixture goes to one of the four sedimentation tanks (respectively with a surface area of 1735, 1035, 1735 and 1990 m^2) after the activated sludge. The purified water separates from the settled sludge through funnel-shaped tanks. The purified water is discharged through the effluent pipe at the Nieuwe Heerenveense Kanaal. The settled sludge is partly traced back to the selectors and the two active sludge spaces. A small portion of the sludge goes as surplus sludge to the thickener.

Drainage of sludge
The liquid sludge, with a dry solid content of approximately 3-4%, is pumped to the sludge dewatering installation where it is further dewatered under high pressure into a sludge cake with ± 24% of dry solid. This sludge cakes were to the end of 1999 deposited in a suitable landfill. Until the end of 2000 these cakes are further processed by a company and composted. Nowadays the sludge cakes are thermally dried and then used as fuel (green energy). The dewatering of sludge is described in section 2.2.

2.1.1 Process block diagram WWTP

To illustrate the process of the wastewater treatment plant a process block diagram is made. The wastewater supply will first go through grid filters with a gap width of 5 mm. The wastewater will then enter the selector and will also be mixed with effluent from the sludge dewatering installation. The wastewater will go through carrousel tanks for aeration treatment. The sludge will settle in the sedimentation tanks and will traced back to the carrousel tank and the selectors. A small part of the sludge goes to the thickener were the dry solid content will be increased. This sludge is dewatered in the sludge dewatering installations.

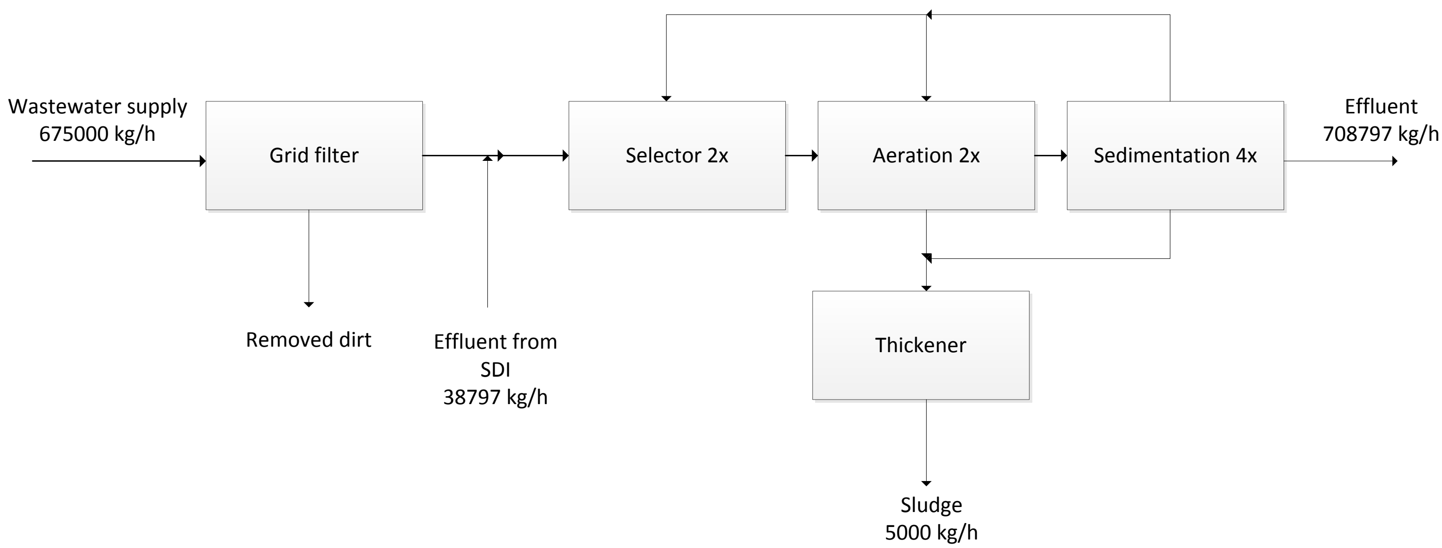

Figure 2 Process block diagram wastewater Treatment Plant

2.2 Sludge dewatering installation

Buffer tanks

The sludge, ± 1100 t/day (1100 m^3/day) is supplied by truck or by ship from all the wastewater treatment plants in Friesland. The generated sludge from the wastewater treatment plant in Heerenveen is supplied by a pipeline. The sludge is deposited in one of the five buffer tanks (each 1000 m^3), where it is mixed until a homogeneous sludge mixture arise. The residence time of the sludge in the buffer tanks has an average of 4.5 days. In figure 3 the feeding tube to the sludge tanks is seen where trucks will discharge the sludge. Every sludge buffer is mixed independently from each other.

Figure 3 Sludge buffer (totally 5000 m^3)

Sludge conditioning

The sludge is pumped to a conditioned buffer (2 x 40 m^3). During pumping iron chloride (40wt%) is added to the sludge, this is called static mixing. $FeCl_3$ is the coagulant and is added in order to flocculate the slurry and thereby make it easier to dewater. After addition of the coagulant, the sludge is stirred in a buffer tank for 30-40 minutes where after it is transported to the filter press. After going through a low and high pressure pump, the flocculant PE is added. Flocculation will occur which makes it able to press the sludge into sludge cakes.

Figure 4 Storage of $FeCl_3$ (40wt%)

Pressing of sludge

Under pressure, up to 15 bar, the conditioned sludge is pumped into the filter presses. There are used a low pressure pump and a high pressure pump. The low pressure pump will transport the sludge with a pressure until 8 bar. Then there will be switched to the high pressure pump which pumps the sludge with a maximum of 15 bar. The sludge remains between the filtering cloths, and the pressed water (filtrate), using a buffer in the basement, will return to the WWTP. Every pressing cycle there is pressed ± 55 m^3 of conditioned sludge. Filling and pressing lasts between 75 and 90 minutes.

After pressing, the chamber filter press with 126 chambers contains an average of 7 ton (79 m^3) sludge cake and the sludge cakes have a dry solid content around 24wt%. The chamber filter press with 154 chambers contains approximately 8.5 ton (8.5 m^3) dry sludge cake. The filter plates have a nap profile and the dry sludge cake (à ± 55 kg per formed sludge cake) falls onto a conveyor belt.

The sludge cakes are transported using a belt to a storage silo (2 x ±100 m^3). The residence time of the sludge cake in the storage silo's has an average of 30 hours. (Slump, 2013)

Figure 5 Left: Low and high pressure pump (respectively green and yellow), Right: Chamber filter press

Taken measures

During pressing an offensive odour is released including ammonia gas. In order to reduce the odour nuisance to a minimum, the presses are completely enclosed. The air is suctioned from the enclosed presses. The exhausted air is treated in bio filters. (www.wetterskipfryslan.nl)

Figure 6 Chamber filter press with casing

Disposal of sludge

From the storage silo, the sludge cakes are deposited in trucks. The sludge cakes (± 170 tons per day, comparable with 9 truckloads) are brought by truck to Swiss-Combi. In the installation of Swiss-Combi the sludge cake will be dried and combusted. (Wetterskipfryslan)

Figure 7 Storage and transportation of sludge cake

2.2.1. Details sludge treatment

In the SDI in Heerenveen they use $FeCl_3$ with a concentration of 40wt% as coagulant. As flocculant a cationic PE 9048FS of 0.15wt% is used. (Slump, 2013)

Table 1: Facts of SDI Heerenveen (2012)

Supplied sludge	45795 kg/h
Dry solid content sludge	3.65wt%
$FeCl_3$ 40wt%	99 kg/h
Dosage $FeCl_3$	58.4 g/kg sludge DSC
Polymer 9048FS 0.15wt%	12 kg/h
Dosage PE	7.07 g/kg sludge DSC
Outlet sludge cake	7 t/h
Dry solid content sludge cake	23.83wt%

In the sludge dewatering installation in Heerenveen there is sludge supplied from 28 different wastewater treatment plants in Friesland, Groningen and Noord-Holland. The sludge is also coming from the islands above the province Friesland. The content of the sludge is not constant and depends on different extern factors like: day of the week, part of the year and weather conditions.

The sludge is coming from:

Akkrum, Ameland, St. Annaparochie, Bergum, Birdaard, Bolsward, Damwoude, Dokkum, Drachten, Franeker, Gorredijk, Grouw, Harlingen , Heerenveen, Joure, Kootstertille, Leeuwarden, Lemmer, Oosterwolde, Schiermonnikoog, Sloten, Sneek, Terschelling, Vlieland, Warns, Wolvega, Workum, Wijnjewoude.

2.3 Overall block diagram

For the overall block diagram the sludge dewatering installation 1 and 2 are taken together. This is done because the processes are overall the same and in this way, at a glance the total in and output can be seen. The temperature is not a constant temperature and therefore a the average temperature in Heerenveen in 2011 and 2012 is taken. The temperature of the sludge and additives are depending on the weather.

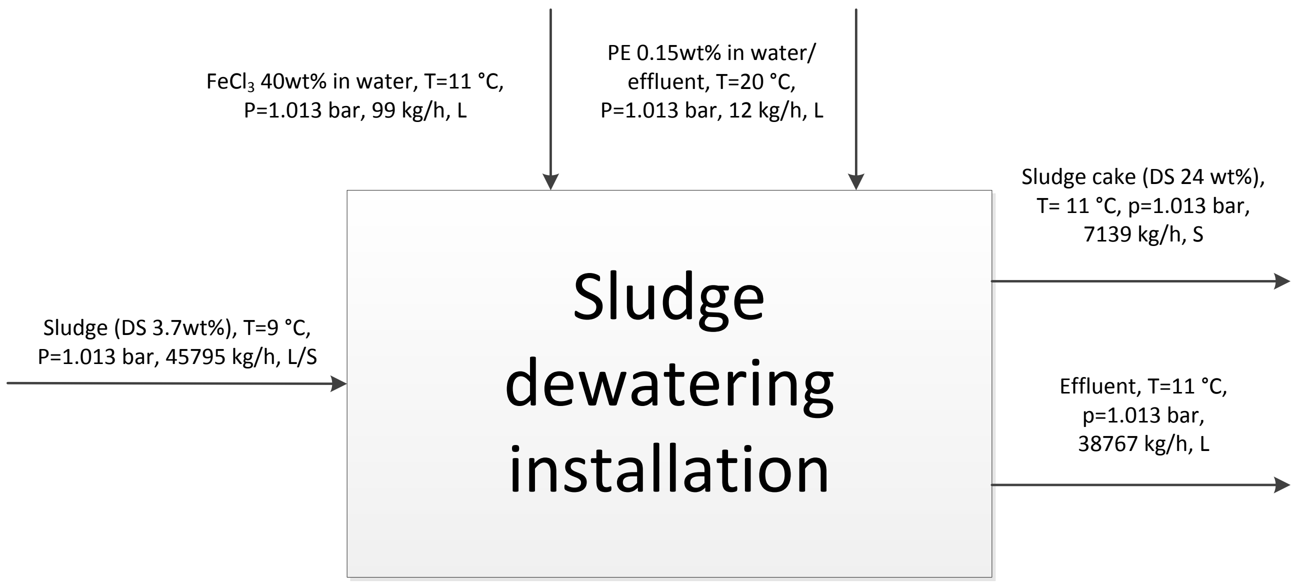

Figure 8 Overall block diagram SDI

2.4 Process block diagram

There are two sludge dewatering installations parallel to each other. The different installations will be referred to as SDI 1 and SDI2 from now on. Both SDIs starts with several sludge buffering tanks, the complete process of SDI1 has a smaller capacity. SDI1 processes around 16.5 m^3/h sludge and SDI2 processes around 20 m^3/h sludge. SDI1 has 2 sludge buffer tanks however SDI2 has 3 sludge buffer tanks. Every tank has a capacity of 1000 m^3 (⌀21.5 m and height 2.75 m). The tanks are stirred with a sludge mixer with a capacity of 10 kW and a propeller ⌀ of 580 mm and 475 rpm. After the sludge buffer in both installations there are two cutters with a capacity of 50m^3/h, so in total 4 cutters. The sludge is pumped with pumps to the conditioned sludge buffer tank. The pumps have capacity of 40 m^3/h and a head of 200 kPa. Every installation has two sludge supply pumps, so 4 in total. After this pump there is ferric chloride added using a dosage pump with a capacity of 1.2 m^3/h and a head of 200 kPa. Every sludge line has one dosage pump, so 2 in every installation and 4 in total. The $FeCl_3$ is stored in a PE/PP tank and the dosage is done using a plastic pipe because it is very corrosive. All the other pipes are made of stainless steel (type 316SS). When the $FeCl_3$ is added, the sludge enters a conditioned buffer tank with a height of 4 m and a content of 40 m^3. Both installations have one buffer, so 2 in total. The buffers are mixed with a sludge mixer with 6 rpm and a capacity of 7.5 kW. The propeller has a diameter of 950 mm. The residence time in the conditioned sludge buffer is 12-17 hours.

The sludge is now pumped with a low and high pressure progressing cavity pump. A progressing cavity pump prevents the sludge flakes to break and is useful for pumping fluids that contain solid particles. The low pressure pump has a capacity of 5-57 m^3/h and a head of 1200 kPa. The high pressure pump has a capacity of 2.5-24 m^3/h and a head of 1500 kPa. Every installation has two low and two high pressure pumps. After these pumps the PE is added with a progressing cavity pump from a PE-intermediate buffer. The PE dilution is done in the basement of SDI2. Between the chamber filter press and the addition of PE is around 12 m distance.

SDI 1 has two chamber filter presses which both have 126 chambers. The total capacity is 10.3 kW. SDI2 has also two chamber filter presses with both 154 chambers. The total capacity is 9.2 kW, all 4 presses has a filtration pressure of 15 bar. SDI 1 has a sludge cake storage silo with a content of 100 m^3 and SDI2 125 m^3. (Slump, 2013) The process flow diagram can be found in section 2.5.

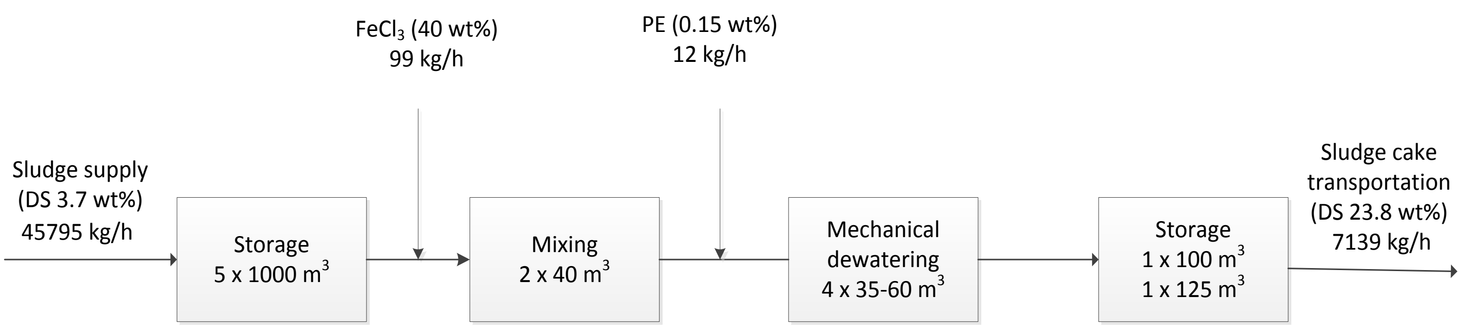

Figure 9 Process block diagram

2.5 Process flow diagram

The process flow diagram of the dewatering installations is seen in figure 10. The process is described in the section above (section 2.4).

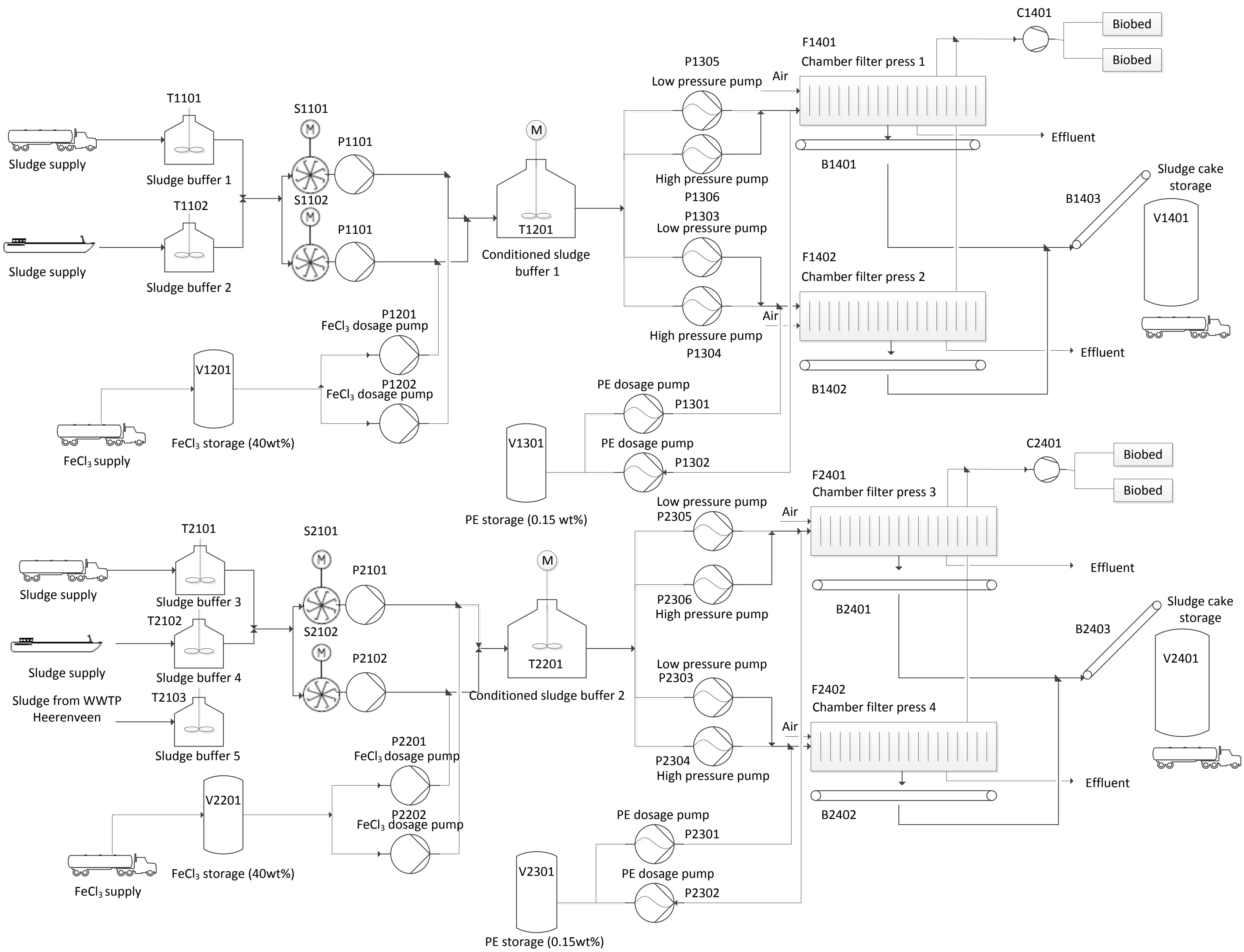

Figure 10 Process flow diagram SDI Heerenveen

2.6 Sludge comparison Garmerwolde and Heerenveen

The sludge of the WWTP in Garmerwolde and the external sludge is digested before the mechanical dewatering step. The sludge in Heerenveen however is a mixture of different sludges. The content of digested sludge is around 30% (from Leeuwarden, Bergum, Drachten, Franeker). The sludge of Heerenveen is coming from total 28 different locations in Friesland and is transported by boat, truck or pipeline. (Slump, 2013)

The experiments are done with sludge from Garmerwolde which is drain after the digesting step and with sludge from Heerenveen which is drain before it is cut into smaller pieces. It’s likely that the difference in appearance can be explained by the fact that the sludge is digested or undigested, and the different place in the system were the sludge is drained. The sludge from Garmerwolde has a black colour and has a delicate structure. The sludge has also a higher viscosity than the sludge from Heerenveen. The sludge from Heerenveen has a more brown colour and contains small pieces of pollution like twigs and hairs. Heerenveen sludge has a much stronger odour than Garmerwolde sludge. This is probably because the organic residue in Garmerwolde sludge is lower because it is digested.

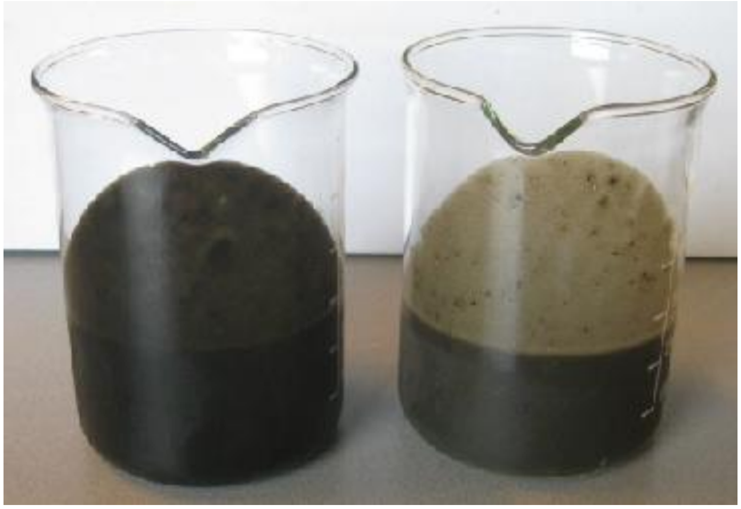

Figure 11 Left: sludge from Garmerwolde, Right: sludge from Heerenveen

3. Theoretical background

3.1 Origin and properties of sludge

Sewage sludge or sludge, is the collective noun for the settleable particles which remain as residue after treatment of waste water. Sludge consist dry solid particles and water containing dissolved matter. The dry solid content is 3-4wt% before dewatering. The dry solid contains organic and inorganic material and are possible to agglomerate to larger units (sludge flocs). In a WWTP arises different sludge's depending on the components and various operations. The following types of sludge can be distinguished:

1. primary sludge
2. secondary sludge
3. tertiary sludge
4. digested sludge
5. chemical sludge

Primary sludge

The first treatment in a WWTP is removal of settable solids from the wastewater by sedimentation. The sediment is called primary sludge. It consists mainly sand and clay particles (inorganic) but also cellulose fibres and other organic residues. The sludge contains also microorganisms that are supplied by the sewage system. Primary sludge has a dry solid content between 0.2-4%.

Secondary sludge

Secondary sludge or biological sludge is the by product that is formed at biological treatment processes such as the activated sludge process, membrane bioreactors and trickling filters. (Bergmans, 2011)The wastewater contains nutrients, nitrogen and phosphate, which will be incorporated in the in the aeration tank by microorganisms. The micro-organisms are mainly bacteria, worms and protozoa, and form the basis of the secondary sludge. Additionally the sludge contains sand- and clay particles and fibres. The amount of the particles is depending on the presence of a grid, sand trap and pre-sedimentation tank. The organic matter content is in the Netherlands around 45-75wt%, depending on simultaneous precipitation. Some bacteria in the sludge produce exocellular material that bridges forms between the bacteria. The bacteria are spherical or thread-forming. Along with higher organisms and dead material they form flakes. When an excess of thread-forming bacteria arise bulky flocs who are difficult to dewater. The composition of secondary sludge depends on the influent composition, the process and the time of year. In the summer secondary sludge is more mineralized (higher ash content) caused by high temperatures than in the winter. A high ash content results mostly in a good effect on dewaterability of sludge. The nitrogen content is 44wt% of the dry solid. Secondary sludge is generally less dewaterable than primary and digested sludge. (Jong, 1998)

Tertiary sludge

Effluent can be treated in a tertiary step for further removal of floating particles, nutrients and micro contaminants using a sand filter. Sludge that will arise after this step is mostly mixed with other sludges and further processed.

Digested sludge

In the waste water treatment plant in Heerenveen is not a digestion step for the sludge. From several sludge suppliers in Friesland there is delivered digested sludge but this is not the biggest part. In Garmerwolde however, all sludge that is dewatered is previously digested. In the digestion 20-50% of the organic compounds are degraded. Digested sludge has a dry solid of around 3.5wt%. In general, digested sludge is easily to dewater. A high content of primary sludge in the sludge digestion is preferably for dewatering the digested sludge.

Chemical sludge

When chemicals are added to sludge, chemical sludge appears. Chemical sludge is almost present in every sludge because a small amount of chemicals are already added in the begin of the purifying process because of unpleasant odours. (Jong, 1998)

3.2 Sludge-water bond

In earlier sections, sludge flocs are mentioned. In this section the composition of the floc will be explained. Sludge always contain a certain amount of dry solid. These dry solid particles can congregate with each other to form flocs. A floc contains also a certain amount of water. Water particles can be bonded on different ways to flocs. There can be divided four types of water in a floc;

Free water, this water has no bonding with the solid particles. It fills the empty spaces between different flocs. Free water is relative easily to remove using gravity.

Colloidal bounded water, sludge contains large amounts of suspended particles and colloids. These particles have a relative large surface and charge. Because of this they have a high ability to bond water. Colloidal water is difficult to remove and acquires a large mechanical power.

Capillary bounded water, this water is located between dry solid particles. How smaller the particles, how larger the capillary forces. For removal of capillary bounded water, large mechanical power is acquired. The adsorbed water can only be removed thermally.

Cellular bounded water, dry solid particles exist of organic and inorganic material. Cellular water is water in the cells of the organisms. This water is impossible to separate with mechanical power. A disruption of the cell wall is necessary, for example by heating. This occurs when sludge is digested. (Jong, 1998)

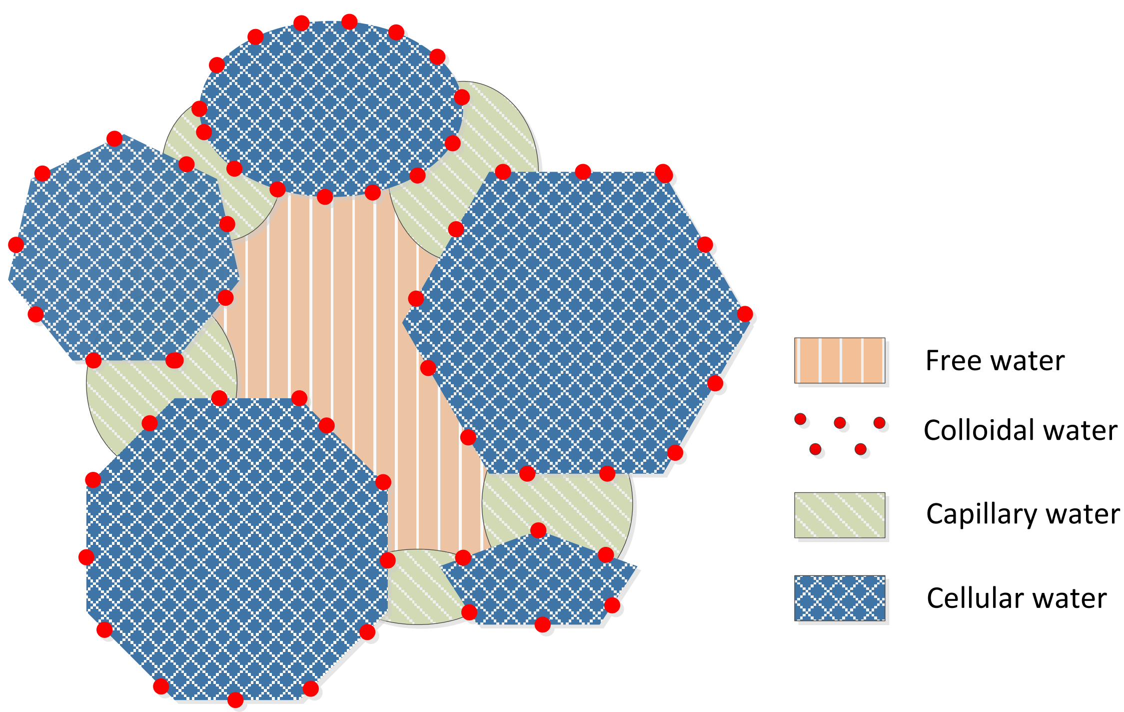

Figure 12 Different types of water in sludge

3.3 Coagulation and flocculation

Coagulation is the process of adding chemical reagents in a mixing device to destabilize (neutralize) colloidal particles. The particles are essentially coated with a chemical sticky layer and allow them to agglomerate or flocculate with other suspended particles to form larger more readily settled particles. Coagulation can been accomplished by many naturally occurring compounds from starch to iron and aluminium salts. (A.J.M. Herwijn, 1995)

The most commonly used coagulants are alum and iron salts and are included in table 2. The multivalent characteristic of these cat ions strongly attracts them to negative charged colloidal particles to neutralize the particles. Their relative insolubility ensures dry solid removal to a high degree. The most frequent used coagulants reacts with calcium bicarbonate. Coagulation reactions are fast and occur in a rapid mixing device. It is essential that the coagulant be dispersed throughout the water to contact and react with the target substances before the coagulant react with water itself in side reactions. If the coagulant react with water it will dissipate some of its coagulating power. (Droste, 1997)

Table 2 Commonly used coagulants (Coagulation and flocculation process fundamentals)

Coagulant	Molecular formula	Formed products	After addition
Alum	$Al_2(SO_4)_3$	$Al(OH)_3$, $CaSO_4$, CO_2	decreases pH
Ferric sulfate	$Fe_2(SO_4)_3$	$Fe(OH)_3$, $CaSO_4$, CO_2	decreases pH
Ferric chloride	$FeCl_3$	$Fe(OH)_3$, $CaSO_4$, CO_2	decreases pH
Ferrous sulfate	$FeSO_4$	$Fe(OH)_2$, $CaSO_4$, CO_2	decreases pH
Sodium aluminate	$Na_2Al_2O_4$	$Al(OH)_3$, Na_2CO_3	increases pH

Flocculators provide gentle agitation of water that has been coagulated to promote particle contact and formation of larger particles. Hydraulic or mechanically driven flocculators may be designed. Flocculators follow the rapid mixing coagulation tank and precede sedimentation and filtration units. Flocculators are added with less intensively mixing than coagulants to prevent breakup of the large floc particles formed.

The flocculation behaviour of sludge adding ferric chloride can be explained by application of the theory of James and Healy. This means that positively charged hydrolysis products of the iron ion is adsorbed to the negatively charged sludge particle. This results in a reverse of the electric potential at the Stern surface of the sludge particle from negative to positive. After adsorption, the sludge can flocculate by attraction between the exposed negative charged sites and coated positively charged sites. Polymerization of iron hydroxide-complexes can lead to the formation of bridges between sludge particles. Bridge forming can also improve flocculation. This results in a decrease of the specific filtration resistance. The dosage at which the potential-reverse point is detected corresponds with the decrease in the filtration resistance. High cationic poly electrolytes adsorb to the sludge particle because of the high electrostatic attraction. With a certain dosage of PE, a potential-reverse will arise. Cationic PE can be thought of as double acting because they are able to act in two different ways: charge neutralization and bridging. (Ravina, 1993)

3.4 Cake filtration theory

The mechanical dewatering process can be divided in two parts, the filtration phase and the expression phase. A sludge cake is formed in the filtration phase, the thickness of the cake increases with the time. In this case there is assumed that the cake behaves as incompressible. The filtration process can be described with the equation of Darcy. The resistance of the filter cake is determined in advance. An amount of water is pressed through the filter medium with certain pressure. This gives a linear mass-time curve, the slope of this curve gives an indication for the resistance of the filter cake. The first term disappears ($C_S = 0$) in Darcy's law (see equation 2). (Herwijn, 2000)

$$t = \frac{\alpha ŋ C_s}{2A^2 \Delta P} V^2 + \frac{ŋ R}{A \Delta P} V \qquad \text{Equation 1}$$

$$R = \frac{t A \Delta P}{V ŋ} \qquad \text{Equation 2}$$

α	Specific filtration resistance	[m kg^{-1}]
ŋ	Viscosity of the filtrate	[Pa s]
Cs	Concentration of solid	[kg m^3]
A	Filtration area	[m^2]
V	Volume of the filtrate	[m^3]
t	Time	[s]
R	Resistance of filter cake	[m^{-1}]
ΔP	Applied pressure difference	[Pa]

		units	(Range) in practice	Expected range
α	Specific filtration resistance	m kg^{-1}	10^{12}-400*10^{12}	10^{12}-10^{16}
ŋ	Viscosity of the filtrate (10°C)	Pa s	1.308*10^{-3}	1.308*10^{-3}
C_s	Concentration of solid	kg m^3	3-30	3-28
A	Filtration area	m^2	414-693*	3.85*10^{-3}
V	Volume of the filtrate	m^3	5000-15000	1.5*10^{-2}-40*10^{-2}
t	Time	s	4500-6600	310
R	Resistance of filter cake	m^{-1}	2.1*10^{12}-1.5*10^{13}	2*10^9*5.4*10^{10}
ΔP	Applied pressure difference	Pa	15*10^5	6.05*10^5

The filtration area depends on the size of the press. The mini press used in the experiments has a filtration area of $3.85*10^{-3}$ m^2 and the SDI of Heerenveen has the biggest chamber filter press with a filtration area of 693 m^2.

The following relationship applies if there is assumed that the second term in equation 1 is negligible with regard to the first term:

$$\frac{dV}{d\ \bar{t}} = constant \qquad \text{Equation 3}$$

The part in the graph of figure 13, where the mass increases linearly with the square roots of the time corresponds with the cake formation phase (see figure 14). The compression phase corresponds with the non-linear part of the graph and is drawn schematically on the right side in figure 14. The equation of Darcy is applied over the linear part of the curve. This gives a value of the specific filtration resistance. The average value of the specific filtration resistance is an indication for the filtration velocity. How lower the filtration resistance how higher the filtration velocity. (Herwijn, 2000) (A.D. Stickland, 2008)

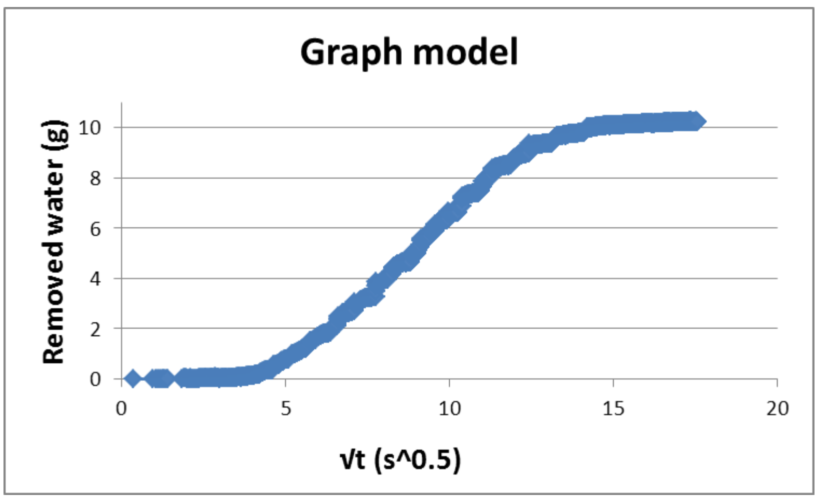

Figure 13 Example of a mass-time curve

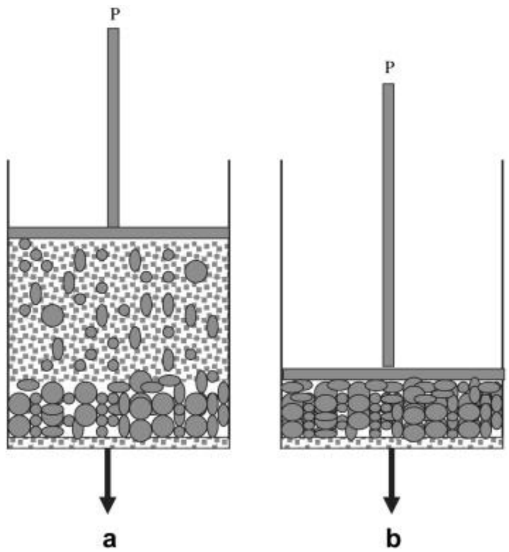

Figure 14 Mechanisms of cake filtration (a) The cake formation stage. (b) The cake compression stage (K.B.Thapa, 2009)

3.5.1 Application of filtration theory at the experimental results

There were made filtration curves of the different experiments. These curves represent the amount of removed water during the mechanical dewatering step versus the time. There is expected a curve what looks like figure 15. The curve is linear in the beginning and almost constant at the end. In the beginning there is not yet a cake of sludge formed and the water can be removed quite easily, the pressure increases to approximately 2 bar in this period. After the cake formation phase, the pressure increases linearly to 6.05 bar. The slope of the corresponding part of the filtration curve will decrease. The slope reaches a value of approximately 0 when almost all the water is removed. It seems to be that there is a relationship between the amount of removed water and the DSC. How higher the amount of water removed during mechanical dewatering , how higher the DSC. However the balance turned out to be very inaccurate. This is the reason that the graphs do not represent the data on a proper way. The graphs were too useless to calculate the specific filtration resistance.

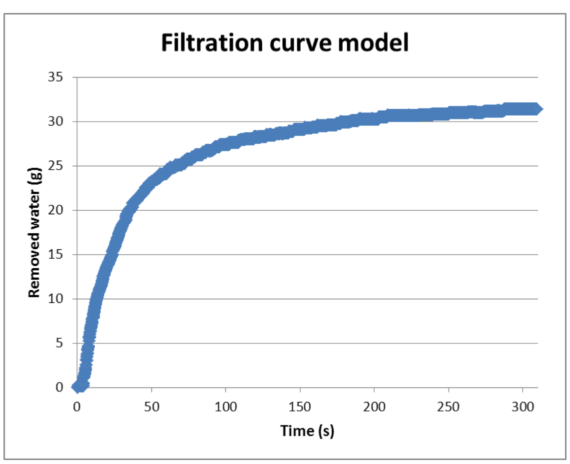

Figure 15 Model of the expected filtration curve

There is a link between the obtained filtration curves (figure 15) and the mass-time curve shown in figure 13. During the experiments the mechanical dewatering system has always the same pressing program. The pressure is build up slowly and after 200 seconds the increase in pressure is at a maximum (see figure 16 c). In figure 16 the three graphs placed next to each other to see their analogy.

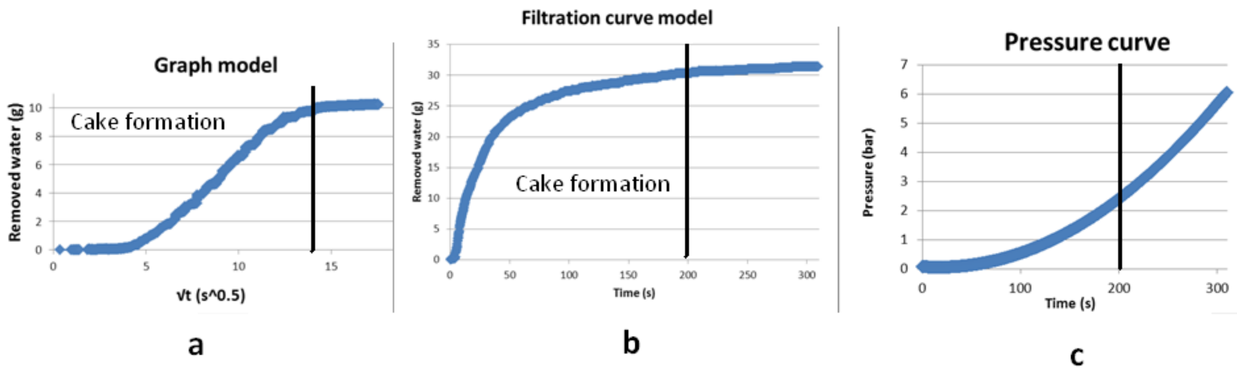

Figure 16 Comparison of the three graphs: a) mass-time curve, b) filtration curve, c) pressure curve

According to the mass-time curve (figure 16 a) and the filtration curve (figure 16 b) there is almost no dewatering anymore after approximately 14 $s^{0.5}$ (200 seconds). However the pressure increases during this period to his final and maximum value of 6.05 bar. This insinuates that the sludge is the compressible phase right now and almost all the water between the sludge flocs is removed. The remained water will stay inside the flocs.

3.5 Reynolds number

The mixing of the sludge and the chemicals is influenced by the Reynolds number. The calculation for the Reynolds number in a tank differs from the calculation in a pipe. The Reynolds number for a flow in a pipe is defined as:

$$Re = \frac{\rho\, v\, D}{\mu} \quad \text{Equation 4}$$

where:

ρ is the density of the fluid (kg/m³)

v is the mean velocity of the object relative to the fluid (m/s)

D is a the diameter of the pipe (m)

μ is the dynamic viscosity of the fluid (Pa·s)

The Reynolds number in a stirred vessel is defined as:

$$Re = \frac{\rho\, N\, D^2}{\mu} \quad \text{Equation 5}$$

where:

N is the angular velocity (rad/s)

The viscosity of sludge is depending on shear stress and is not constant. Because the dry solid content is not very high before addition of coagulants and flocculants, the sludge is assumed to have the same viscosity as water. After the addition of $FeCl_3$ the sludge will still have approximately the same viscosity. When PE is added, the viscosity will increase and is assumed to be equal to the viscosity of glycerine (Pumplocker).

Table 3 Values for calculation Reynolds number

stirring velocity (rpm)	6
stirring velocity (rad/s)	0.628319
density (kg/m^3)	1000
diameter pipe (m)	0.15
viscosity water(Pa*s)	0.001308
viscosity glycerine (Pa*s)	0.0045

The Reynolds numbers are calculated in the conditioned sludge buffer, before flocculation and after flocculation. The Reynolds number in the conditioned sludge buffer is >10000 and therefore fully turbulent. This means that the sludge buffer is stirred well. The Reynolds number before flocculation is three times higher than after the addition of PE. Both Reynolds numbers indicate a turbulent flow.

Table 4 Calculated Reynolds numbers

Reynolds number coagulation tank	433531
Reynolds number before flocculation	99145
Reynolds number after flocculation	28818

4. Method

4.1 Dry solid determination

This method is used for calculating the dry solid content of pure sludge:

- Weigh an empty aluminium cup.
- Tare the balance and weigh approximately 50.0 grams of sludge. (It is important to use always the same amount of sludge (maximum ± 0.05 g), the dry solid content is slightly different when you use another amount of sludge.)
- Put the aluminium cup with the sludge in the oven for 24 hours at 105◦C. The dry solid content will not change anymore after 24 hours.
- Weigh the aluminium cup with the dry sludge.
- Subtract the weight of the empty aluminium cup from the cup with the dry sludge to obtain the weight of the dry sludge.
- Divide the weight of the dry sludge by the amount of wet sludge and multiply by 100% to obtain the dry solid content.

4.2 Flocculation frame

- Dilute the pure sludge to a 50wt% solution with tap water.

- Use a magnetic stirring plate to carefully mix the coagulant and the sludge. It is important to stir carefully and short, because the formed flocks should stay intact. If the stirring bar is not able to stir the whole mixture, use a spoon to stir the solution manually. Make 700 ml 50wt% sludge.
- Divide the solution over the six test tubes (100 ml in each tube). There is made 700 ml solution instead of 600 ml solution to be sure that the mixture is homogeneous.
- Add flocculant with the syringe in each test tube.
- Close the test tubes with the plugs.
- Turn the flocculation frame carefully upside down for 2 times. The formed flocks should stay intact.
- Remove the plugs.
- Let the mixture rest for a certain time because it takes a while before the flocculation is completed.

Figure 17: Flocculation with different sludge concentrations (Stoffelsma, 2012)

4.3 Mechanical dewatering

- Use pure sludge.
- Add the flocculant and coagulant at the same time.
- Stir for 3 seconds with a mechanical stirrer (figure 18). Set the mechanical stirrer at 1600 rpm, the speed will rise in 3 seconds from approximately 1100 rpm to 1600 rpm.
- Let the mixture settle for a couple of minutes according to table 5.
- Filter the sludge over a Büchner funnel (without vacuum).

- Weigh the filtrate.
- Weigh 50 grams of sludge and pour it in the press setup (see Appendix III).
- Set the pressure program and turn it on, the pressing time is always 310 seconds.
- Weigh the obtained cake of sludge and the filtered water.
- Put the cake in the oven for 24 hours at 105°C.
- Weigh the dry cake.
- Determine the dry solid content by dividing the weight of the dry cake by the weight of the wet cake and multiplying it by 100%.

Figure 18 Left: press, right: mechanical stirrer

Table 5 Settle time of different coagulants

Coagulant	Settle time in minutes
$FeCl_3$	5
$MgCl_2$	15
$Mg(OH)_2$	15

5. Results and discussion

Because earlier experimental studies showed that the dry solid content depends on different factors, there was repeated an experiment with the same reaction conditions three times. The factors that should be held constant are, the amount of coagulant and flocculant, the amount of sludge that goes into the press and the oven time. A triplo experiment was performed with $FeCl_3$ as coagulant.

The triplo measurement didn't give exactly the same dry solid contents. There is a variation of ± 1% in the dry solid content. From now on duplo measurements should be done because this is more accurate than single measurements. Triplo measurements would be probably even better but because of limited time this was not possible. From the duplo measurements the average dry solid content should be calculated.

5.1 $FeCl_3$ as coagulant

5.1.1 Garmerwolde sludge

The dosage of $FeCl_3$ is varied and the amount of PE is held constant. The reaction conditions can be found in table 6.

Table 6 Reaction conditions Garmerwolde sludge with $FeCl_3$

sludge (ml)	$FeCl_3$ 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	5	25	17,68
100	6	25	19,45
100	7,5	25	23,31
100	10	25	25,07
100	15	25	30,06

Figure 19 shows the obtained dry solid contents with a varying dosage of $FeCl_3$. The maximum dry solid content is not reached yet. With adding $FeCl_3$ as coagulant, a high dry solid content can be reached. With addition of 15 ml $FeCl_3$, the dry solid content is 30% and this is probably still not the highest dry solid content that can be reached. There is not added more flocculant because the dosage on sludge dry solid content will become too high. For the waste water plant it's necessary to add not too much $FeCl_3$ because this will also contaminate the water. In the WWTP of Garmerwolde there is used 65 g/kg sludge DSC. Addition of 15 ml of $FeCl_3$ corresponds with 167.5 g/kg sludge DSC and gives a high dry solid content. However this dosage is not preferable for the WWTP because it is almost three times higher than the used dosage.

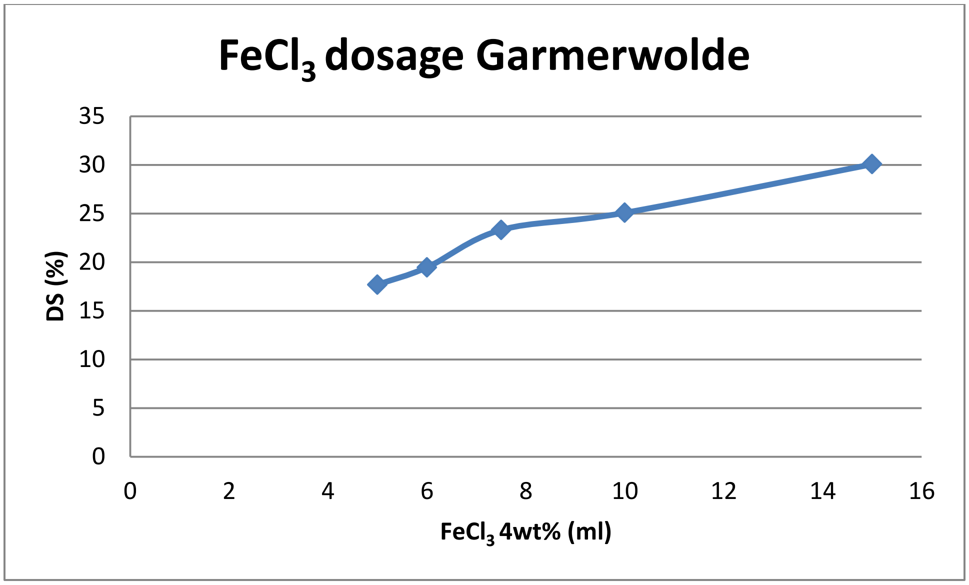

Figure 19 Finding the optimum dosage of $FeCl_3$ for Garmerwolde sludge

During the experiments the balance showed to be inaccurate. Therefore the pressed water is also weighted manually to check how much water was removed during the mechanical dewatering. Figure 20 shows a good filtration curve for a dosage of 15 ml $FeCl_3$. According to table 1 in appendix I, there is removed 27.37 g of water (average value) using 7.5 ml coagulant. Figure 20 shows that there is removed almost 30 g of water. Comparing the dosage of 15 ml coagulant there is removed 30.93 g of water (average), therefore the pressing curve of 305 is assumed to be incorrect. After this assumption we can concluded that how higher the DSC is, how more water is removed after mechanical dewatering.

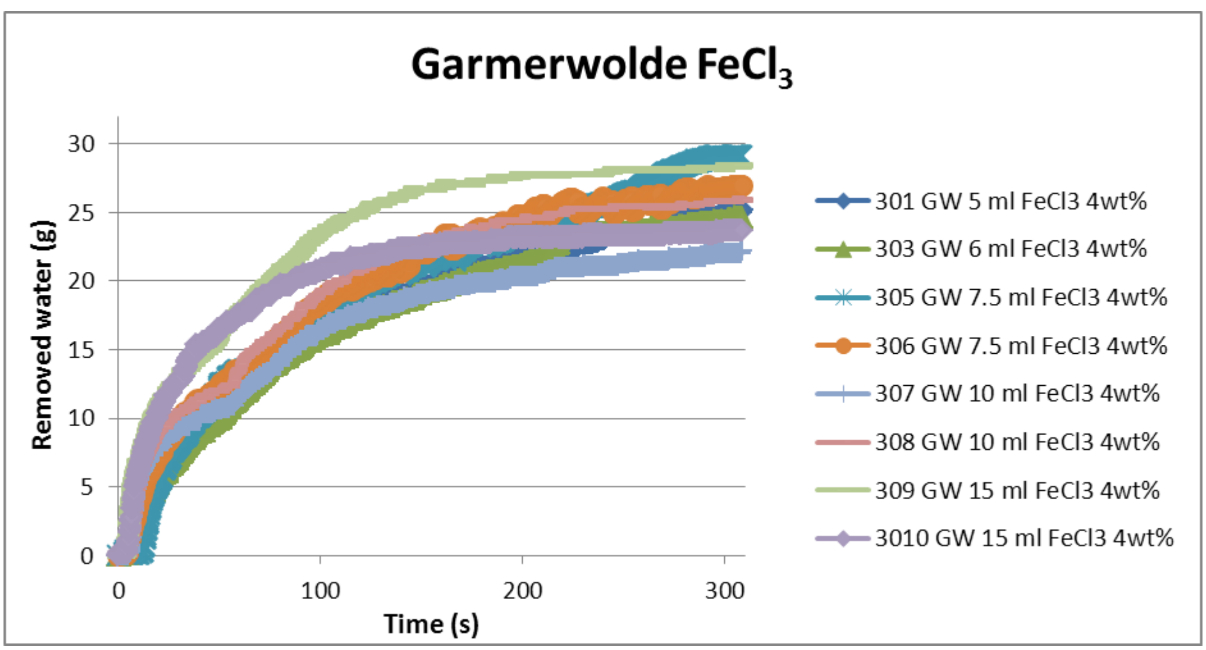

Figure 20 Removed water during mechanical dewatering of Garmerwolde sludge with $FeCl_3$

5.1.2 Heerenveen sludge

The dosage of $FeCl_3$ is also varied with Heerenveen sludge. However there are added more doses and smaller amounts because after some experiments it was seen that an addition of 7.5 ml gives a high DSC. The reaction conditions are showed in table 7.

Table 7 Reaction conditions Heerenveen sludge with $FeCl_3$

sludge (ml)	FeCl3 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	4	25	20,40
100	5	25	22,17
100	6	25	22,95
100	7	25	26,76
100	7,5	25	27,42
100	8	25	25,78
100	10	25	16,62

The highest dry solid content is reached by adding 7.5 ml (88.5 g/kg sludge DSC) $FeCl_3$ (4wt%) and 25 ml PE according to table 4 and figure 21. In the SDI in Heerenveen a dosage of 58 g/kg sludge DSC is used. Adding more $FeCl_3$ is probably an excess and results in a lower DSC and is more difficult to filter.

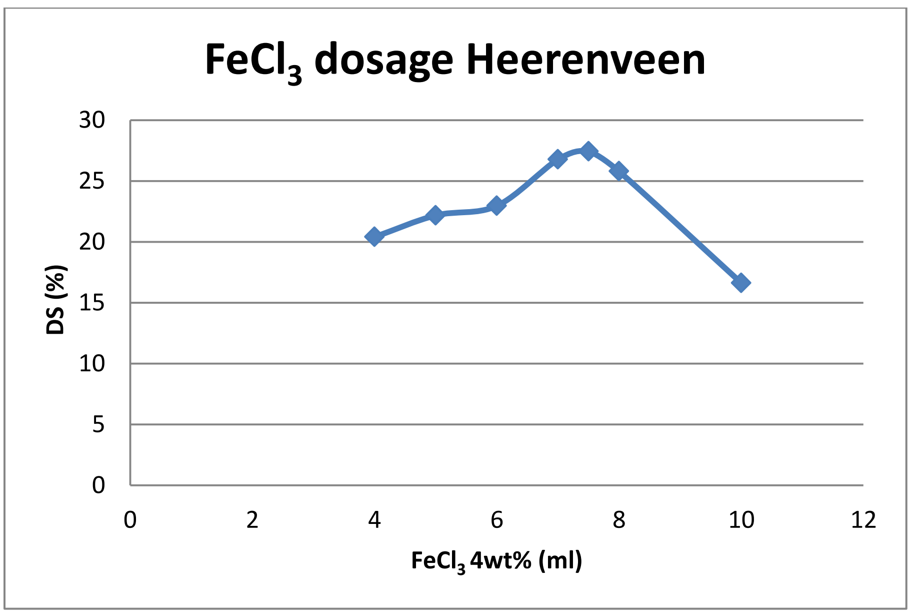

Figure 21 Finding the optimum dosage of $FeCl_3$ for Heerenveen sludge

When the dry solid contents are compared with the filtration curves it looks like this doesn't corresponds. Normally a higher dry solid content corresponds to a high value of removed water after mechanical dewatering. However in figure 22 it is shown that there is removed almost the same amount of water with an addition of 7.5 ml and 10 ml $FeCl_3$. There is a big difference in dry solid content using 7.5 ml and 10 ml $FeCl_3$, respectively 27.42 % and 16.62%.

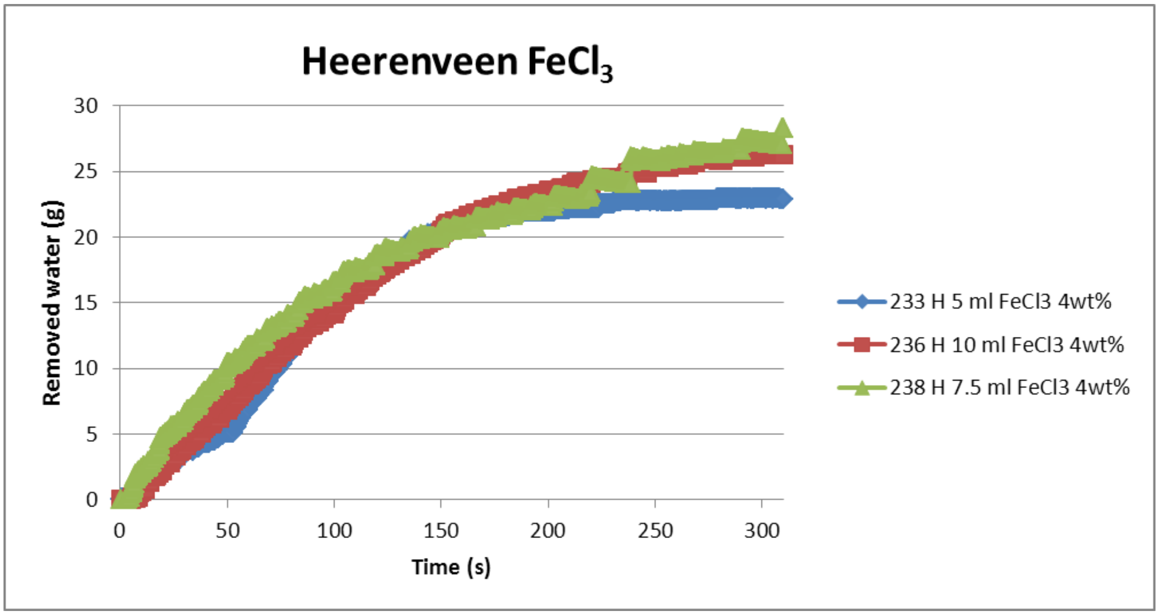

Figure 22 Removed water during mechanical dewatering of Heerenveen sludge with $FeCl_3$

The same filtration curves of 7.5 ml and 10 ml dosages $FeCl_3$ in graph 5 can be explained by looking at table 8. With an addition of 10 ml $FeCl_3$ there were no flocs, or very small flocs, formed and there couldn't be water removed by filtration. Therefore there was still a large amount of water in the sludge solution that was pressed. Because the flocs were small, the water could easily be pressed.

With an addition of 7.5 ml $FeCl_3$ there are only small flocs formed but there is already some water removed during filtering. After mechanical dewatering there is removed the most water when comparing to the other dosages of $FeCl_3$. This results in a thin cake which has a high dry solid content.

Table 8 Removed water with different dosages of $FeCl_3$ with Heerenveen sludge

$FeCl_3$ (ml)	water after filtering (g)	water after pressing (g)	water totally removed (g)
5	62,58	25,48	88,07
7,5	18,42	34,70	53,12
10	0,00	30,49	30,49

5.1.3 Differences between Garmerwolde and Heerenveen

Comparing the dosage of $FeCl_3$ to Garmerwolde and Heerenveen sludge there is a big difference. With Heerenveen sludge, the highest dry solid content is reached with 88.5 g/kg sludge DSC. But with Garmerwolde sludge the optimum DSC isn't reached yet by adding 167.5 g/kg sludge DSC. The dry solid curve of Heerenveen is with a clear optimum meanwhile the DSC curve of Garmerwolde is almost linear. Probably there will also be an optimum but this is not reached yet.

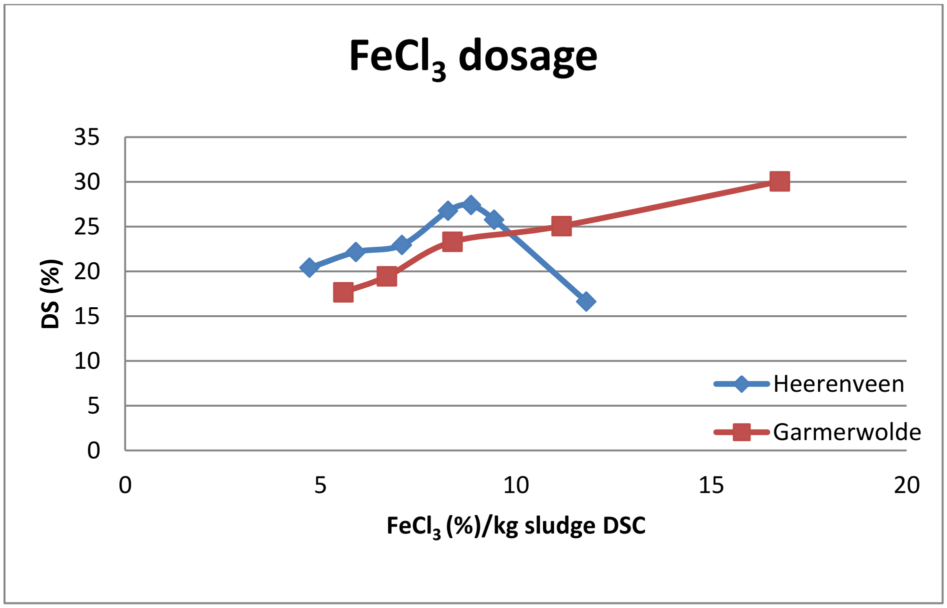

Figure 23 Comparison of DSC using $FeCl_3$ between Garmerwolde and Heerenveen

5.2 $MgCl_2$ as coagulant

To obtain the concentration of $MgCl_2$ that can be used best in the experiments, there is done an experiment with Garmerwolde sludge. The conditions and dry solid content of the experiments can been found in table 9.

Table 9 Conditions $MgCl_2$ experiments for determination of concentration

	sludge (ml)	g/kg sludge	mL PE (0.1wt%)	% DS
10 mL $MgCl_2$ (8wt%)	100	229.6	20	18,91
10 mL $MgCl_2$ (4wt%)	100	111.2	20	22,31

Using a 8wt% solution of $MgCl_2$ gives a lower DSC than a 4wt% solution. To do a good comparison between the coagulants ($FeCl_3$, $MgCl_2$ and $Mg(OH)_2$), it is better when the concentrations are the same. Because the solution of 4wt% gave better results and is better comparable with other coagulants the concentration of $MgCl_2$ should be 4wt%. Also for other coagulants a 4wt% solution is used for both Garmerwolde sludge and Heerenveen sludge.

5.2.1 Garmerwolde sludge

The optimum dosage PE using $MgCl_2$ as coagulant is 25 ml (6.74 g/kg sludge DSC) according to table 10 and figure 24. For further experiments with $MgCl_2$ there is used a dosage of 25 ml PE (0.1wt%).

Table 10 Conditions to determine optimum dosage of PE

sludge (ml)	$MgCl_2$ 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	10	15	18,83
100	10	20	20,32
100	10	25	21,18
100	10	30	18,55

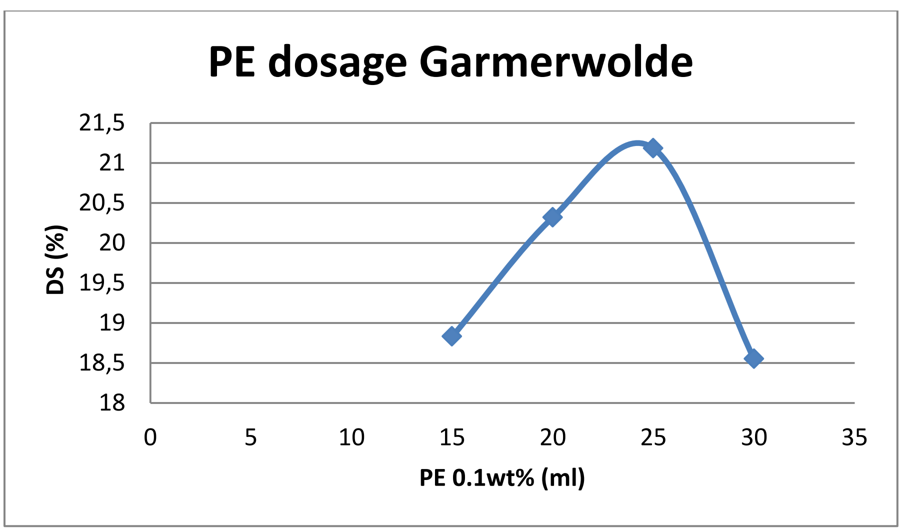

Figure 24 Finding optimum PE dosage using $MgCl_2$ and Garmerwolde sludge

The optimum dosage of $MgCl_2$ should also be determined. Therefore the dosage of $MgCl_2$ should be varied in experiments. The reaction conditions are showed in table 11.

Table 11 Conditions to determine optimum dosage of $MgCl_2$.

sludge (ml)	$MgCl_2$ 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	5	25	19,60
100	10	25	20,88
100	15	25	22,23
100	20	25	18,90
100	25	25	17,27
100	30	25	17,78

In figure 25 it is shown that there is an optimum for addition of 15 ml $MgCl_2$ (166.4 g/kg sludge DSC). The expectation is that a higher DSC can be reached when the settle time increases with a couple of hours. $MgCl_2$ will form struvites with phosphates that are present in the sludge. (P.Fattah, 2012)

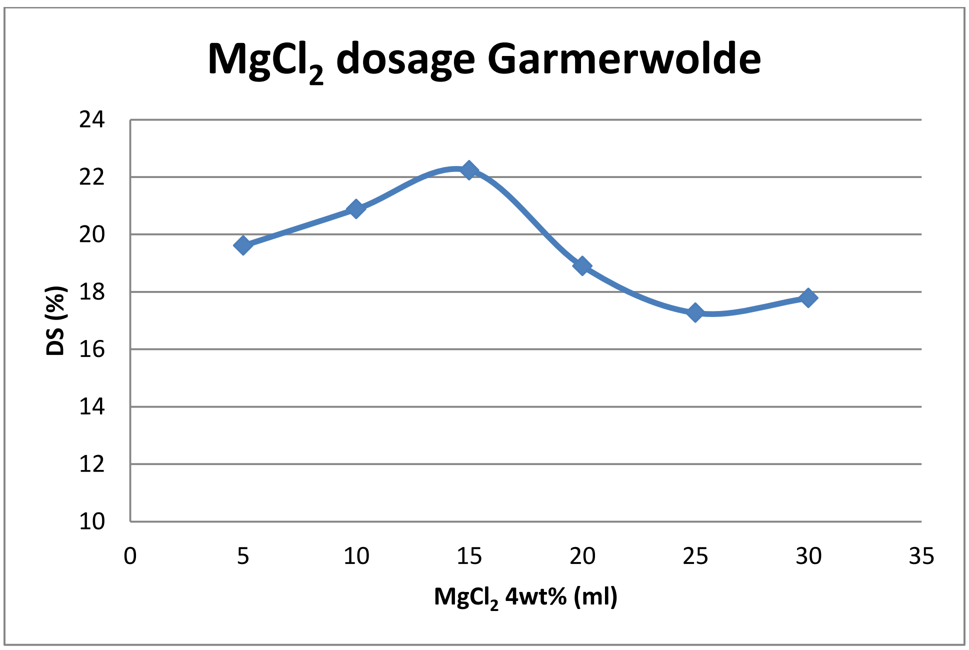

Figure 25 Finding optimum dosage $MgCl_2$ with Garmerwolde sludge

According to figure 26 the water that is removed during mechanical dewatering corresponds with the height of the DSC. The most water is removed from the sludge were 15 ml $MgCl_2$ was added. Were there was added more $MgCl_2$ there was observed an excess and the resulting dry solid contents were low. In graph 27 it is shown that there is never removed more water than 18 grams using more than 20 ml $MgCl_2$.

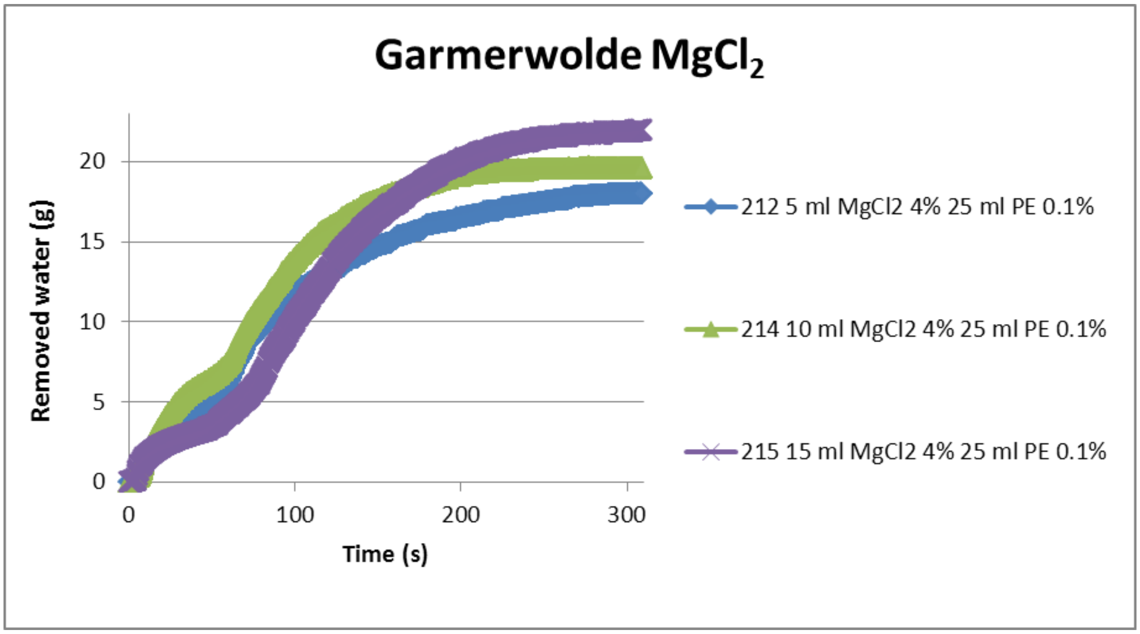

Figure 26 Removed water during mechanical dewatering of Garmerwolde sludge with $MgCl_2$

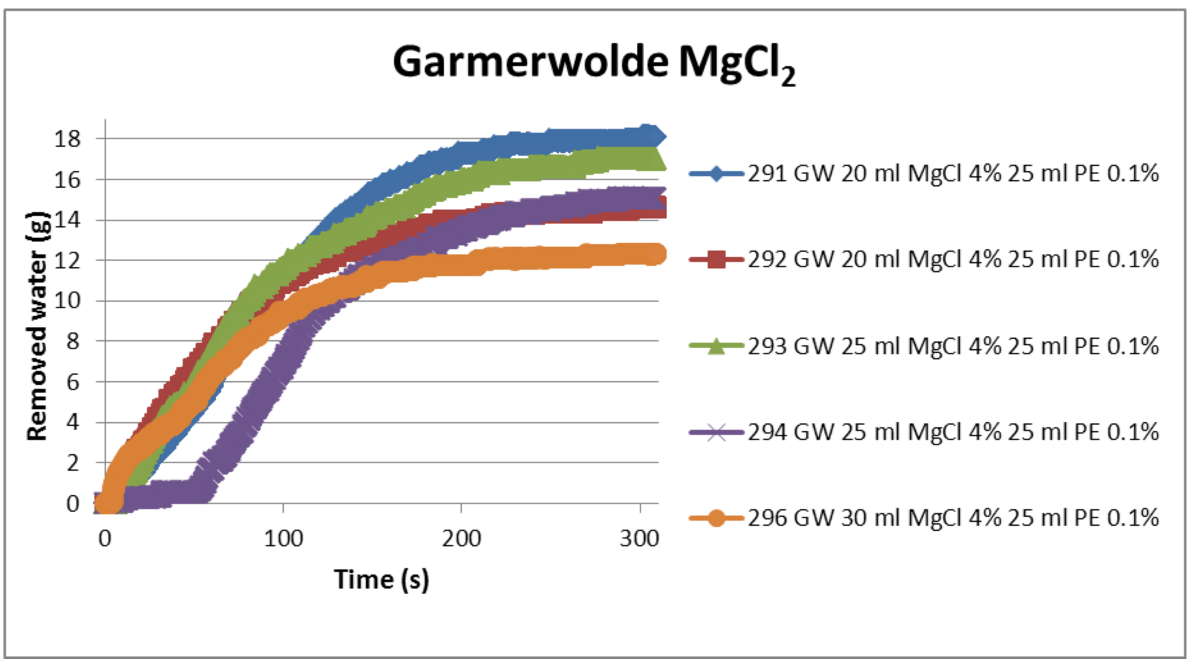

Figure 27 Removed water during mechanical dewatering of Garmerwolde sludge with $MgCl_2$

5.2.2 Heerenveen sludge

The same experiments for determining the dosage of PE are done with sludge from Heerenveen. The optimum dosage for PE is 25 ml (7.12 g/kg sludge DSC).

Table 12 Conditions to determine optimum dosage of PE

sludge (ml)	$MgCl_2$ 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	15	15	17,21
100	15	20	18,44
100	15	25	19,31
100	15	30	16,85

In figure 28 it is shown that the optimum dosage for PE is 25 ml using $MgCl_2$ as coagulant. Comparing the removed water from figure 29 and the optimum dosage, there can be concluded that the most water is removed from the 25 ml dosage PE that has also the highest DSC.

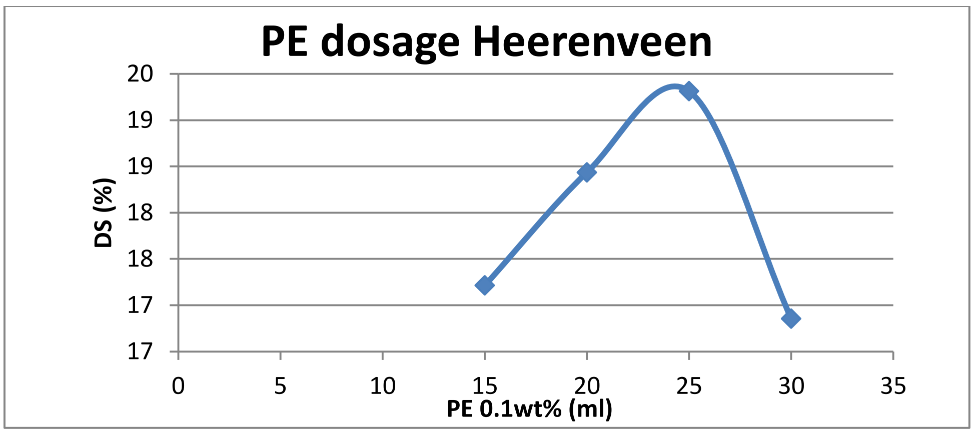

Figure 28 Finding optimum PE using $MgCl_2$ and Heerenveen sludge

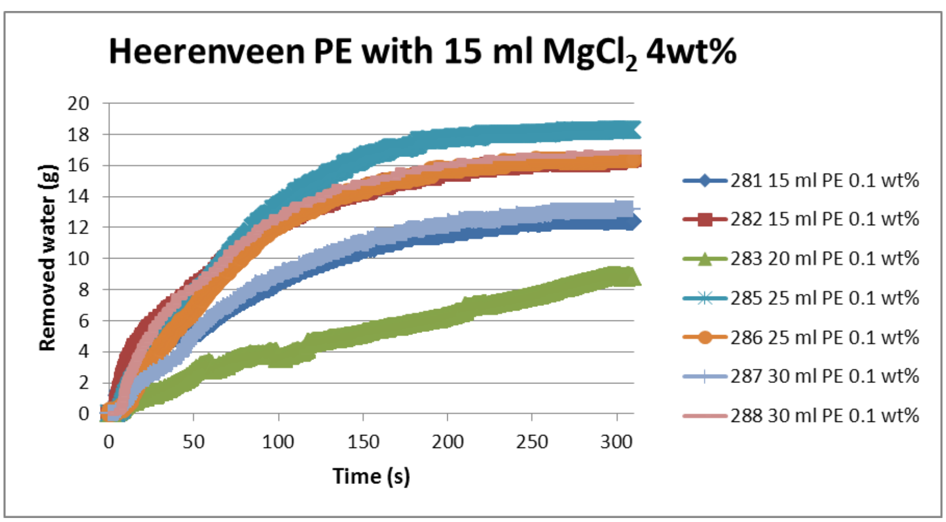

Figure 29 Removed water during mechanical dewatering of Heerenveen sludge with $MgCl_2$

The optimum dosage for PE is determined but the optimum for $MgCl_2$ should also be determined. The amount of $MgCl_2$ is varied and can be found in table 13.

Table 13 Conditions to determine optimum dosage of $MgCl_2$.

sludge (ml)	$MgCl_2$ 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	4	25	19,88
100	5	25	18,75
100	7,5	25	19,10
100	10	25	18,91
100	15	25	20,42
100	20	25	22,66
100	25	25	15,70
100	30	25	18,98

Figure 30 shows that there is an optimum for addition of 20 ml $MgCl_2$ (235.0 g /kg sludge DSC). The expectation is that a higher DSC can be reached when the settle time increases with a couple of hours because there will be more struvite forming. According to graph 31 there is also removed the most water during the mechanical dewatering step when there is used 20 ml $MgCl_2$. The lowest DSC is obtained when there is added 25 ml $MgCl_2$ and 25 ml PE. Comparing this with the removed water during mechanical dewatering, it corresponds to the lowest value according to figure 27 in. Probably we can conclude that how more water is removed during mechanical dewatering, how higher the DSC.

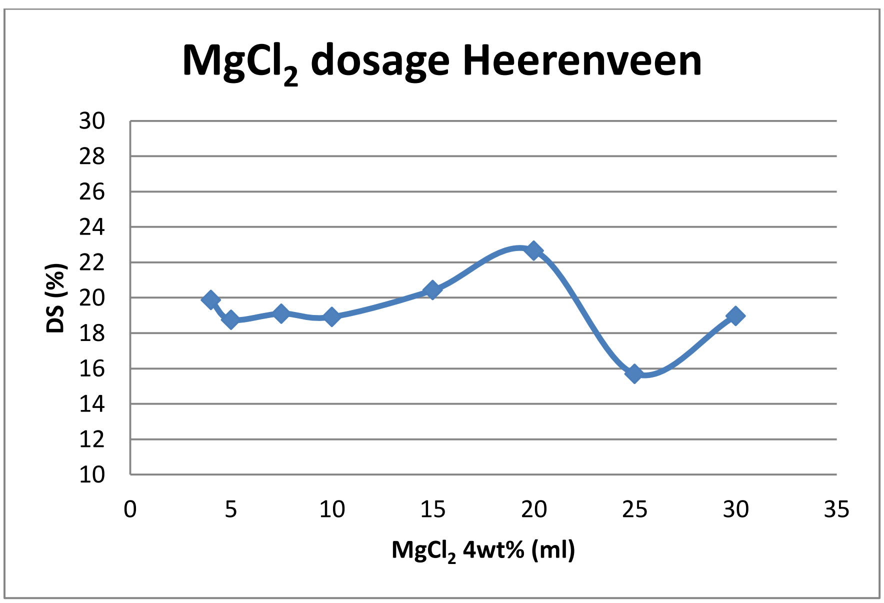

Figure 30 Finding optimum dosage $MgCl_2$ with Heerenveen sludge

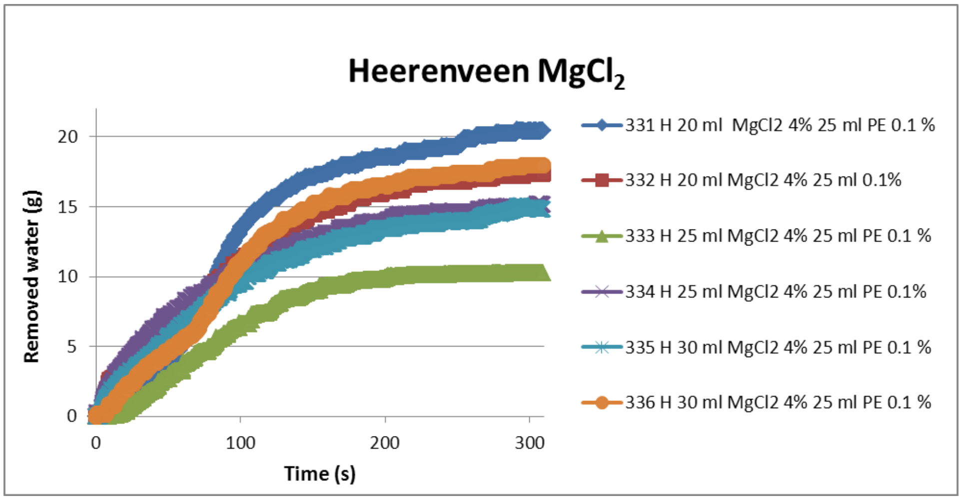

Figure 31 Removed water during mechanical dewatering of Heerenveen sludge with $MgCl_2$

5.2.3 Differences between Garmerwolde and Heerenveen

According to figure 24 and 28 the highest DSC are obtained when 25 ml of PE is used both for Garmerwolde and Heerenveen sludge. However, this does not mean that the dosage of PE is the same. The dosage varies because the sludge of Garmerwolde has a different DSC than the sludge of Heerenveen. The dry solid values are respectively 3.71wt% and 3.51wt%. The PE dosages corresponds to 6.74 g/kg sludge DSC for Garmerwolde and 7.12 g/kg sludge DSC for Heerenveen.
The optimum dosage of $MgCl_2$ for Garmerwolde is 166.4 g/kg sludge DSC and for Heerenveen 235.0 g/kg sludge DSC according to figure 32. Figure 32 illustrates clearly that the DSC that can be reached with $MgCl_2$ is the same for both sludge's 22-25wt% but a different dosage is necessary to reach this dry solid content. With Heerenveen sludge there should be used more $MgCl_2$.

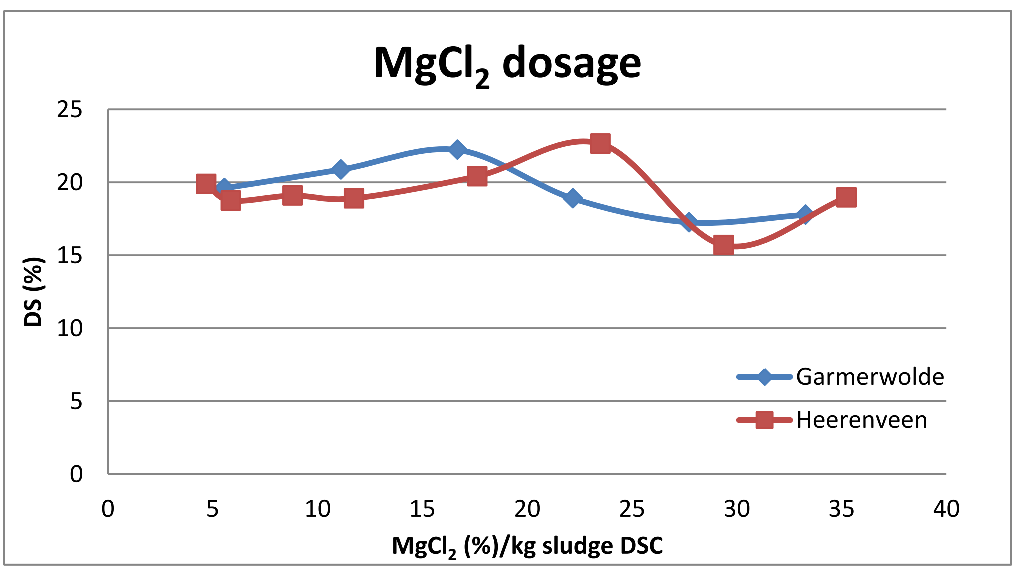

Figure 32 Comparison of DSC using $MgCl_2$ between Garmerwolde and Heerenveen

5.3 $Mg(OH)_2$ as coagulant

5.3.1 Garmerwolde sludge

The optimum dosage PE using $Mg(OH)_2$ as coagulant is 20 ml (6.74 g/kg sludge DSC) according to table 14 and figure 33. Despite the higher DSC using 20 ml of PE there is decided to use 25 ml of PE to make better comparisons with the other experiments.

Table 14 Conditions to determine optimum dosage of PE

sludge (ml)	$Mg(OH)_2$ 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	10	10	4,91
100	10	15	12,08
100	10	20	22,49
100	10	25	15,92
100	10	30	17,62

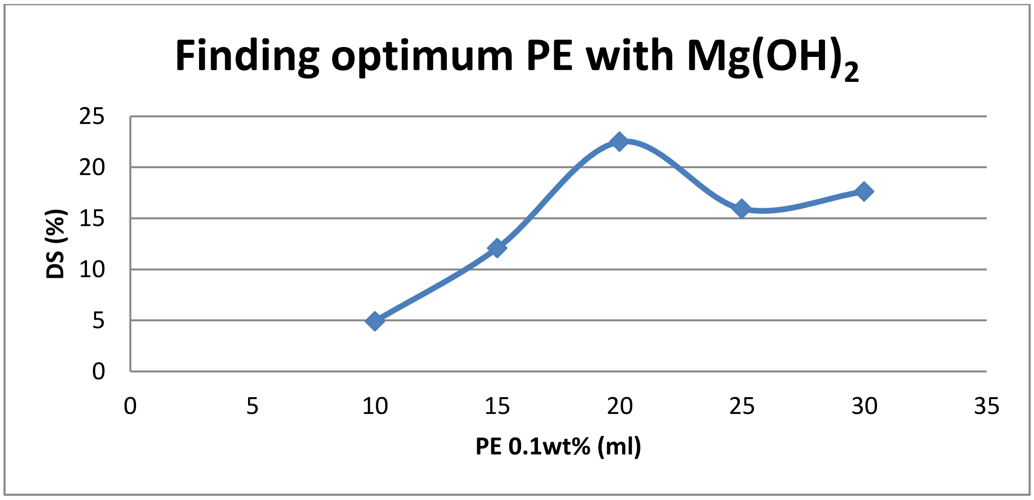

Figure 33 Determination dosage PE with $Mg(OH)_2$ Garmerwolde sludge

A right dosage of $Mg(OH)_2$ should be determined and there is used 25 ml PE as flocculant. The reaction conditions with a variation in the amount of $Mg(OH)_2$ can be found in table 15.

Table 15 Conditions to determine optimum dosage of $Mg(OH)_2$

sludge (ml)	$Mg(OH)_2$ 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	5	25	21,43
100	10	25	19,82
100	15	25	21,21
100	20	25	21,06
100	25	25	18,62
100	30	25	24,40

It is hard to give a proper recommendation with regard to the dosage of $Mg(OH)_2$.
The coagulation and flocculation are probably not completed yet, that is why figure 34 does probably not represent the best dosage of $Mg(OH)_2$. The expectation is that the best dosage can be obtained when the settle time increases with a couple of hours. For now the best dosage of $Mg(OH)_2$ with a settle time of 15 minutes is 30 ml, the thinnest cake (1.3 mm) was obtained with this dosage as well (see table 6 in appendix I). According to table 6 in appendix I and figure 35 also the amount of removed water during the mechanical dewatering step is the highest when a dosage of 30 ml is used.

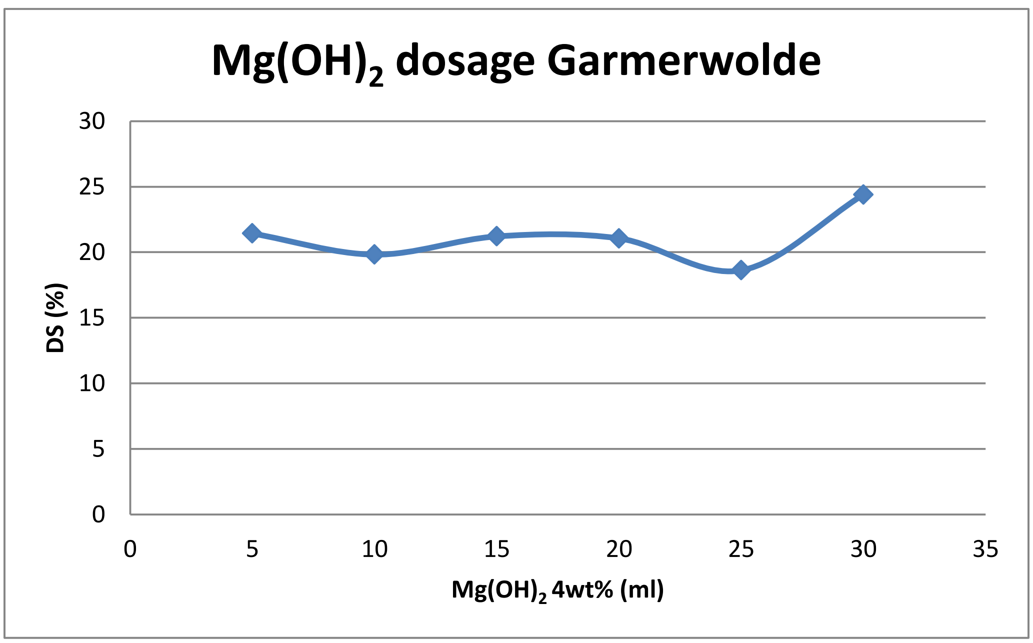

Figure 34 Finding optimum dosage $MgCl_2$ with Heerenveen sludge

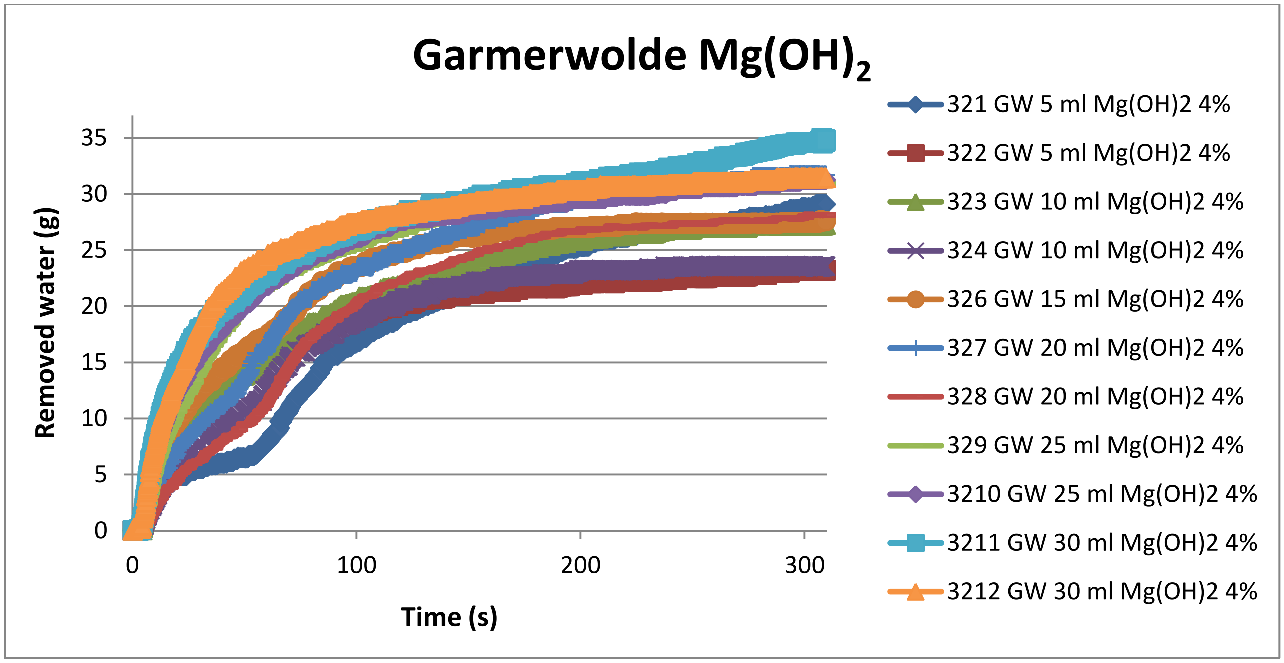

Figure 35 Removed water during mechanical dewatering of Garmerwolde sludge with $Mg(OH)_2$

5.3.2 Heerenveen sludge

The optimum dosage of PE for $Mg(OH)_2$ is between the 20 and 25 ml (5.7 and 7.12 g/kg sludge DSC). There is used 25 ml of PE to determine the optimum dosage of $Mg(OH)_2$ because in experiments with other coagulants the same amount of PE is used. Besides this, there is just a slightly difference between the dry solid contents of 20, 25 and 30 ml of $Mg(OH)_2$.

Table 16 Conditions to determine optimum dosage of PE

sludge (ml)	$Mg(OH)_2$ 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	10	15	13,69
100	10	20	16,82
100	10	25	16,57
100	10	30	16,51

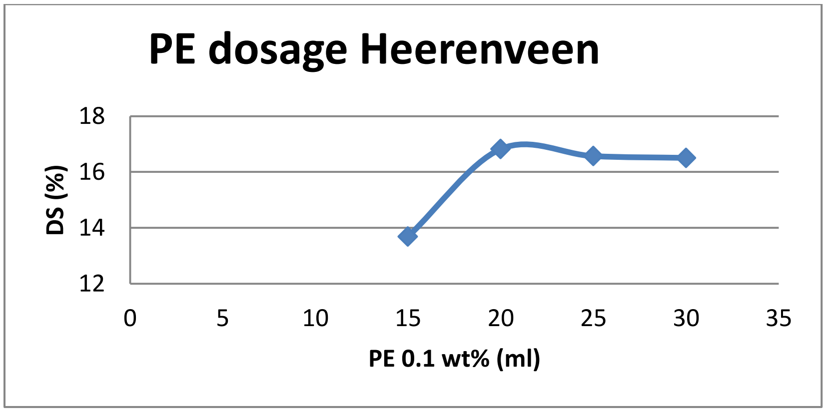

Figure 36 Determination dosage PE with $Mg(OH)_2$ Heerenveen sludge

Another reason why there is chosen for a dosage of 25 ml instead of 20 ml is because the filtration curves of 25 ml are much better. Figure 37 shows the filtration curves and it is clear that the orange en blue line shows the best curves (both filtration curves of 25 ml PE addition).

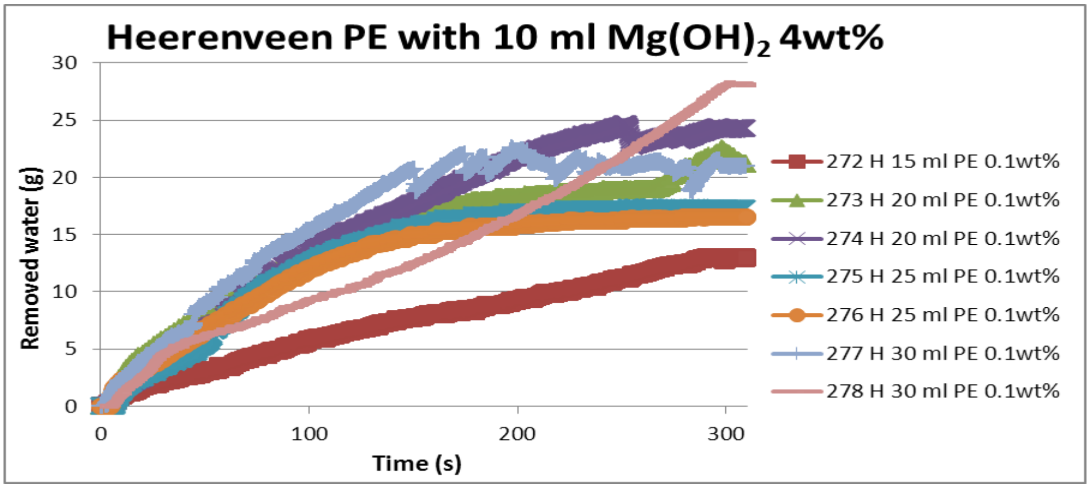

Figure 37 Removed water during mechanical dewatering of Heerenveen sludge with $Mg(OH)_2$

The optimum dosage for $Mg(OH)_2$ with Heerenveen sludge should be determined by varying the dosage. The reaction conditions can be found in table 17.

Table 17 Conditions to determine optimum dosage of $Mg(OH)_2$

sludge (ml)	$Mg(OH)_2$ 4wt% (ml)	PE 0.1wt% (ml)	% DS
100	5	25	17,26
100	10	25	18,47
100	15	25	19,22
100	20	25	19,21
100	25	25	20,39
100	30	25	21,48

There is not ready reached an optimum of $Mg(OH)_2$ because the coagulation and flocculation is probably not completed yet. The highest dry solid content will probably be reached by letting the sludge have more settle time before pressing.

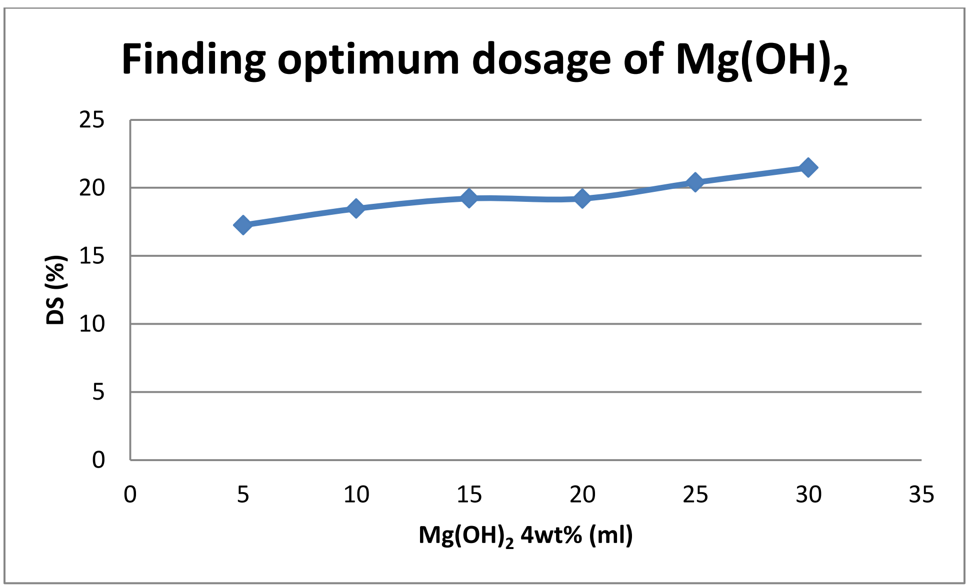

Figure 38 Determination dosage $Mg(OH)_2$ Heerenveen sludge

It is difficult to see an optimum with $Mg(OH)_2$ as coagulant. Both curves don't show an optimum because the coagulation and flocculation is probably not completed yet. Figure 39 shows that with Garmerwolde sludge the dry solid content is slightly higher than the dry solid content of Heerenveen sludge.

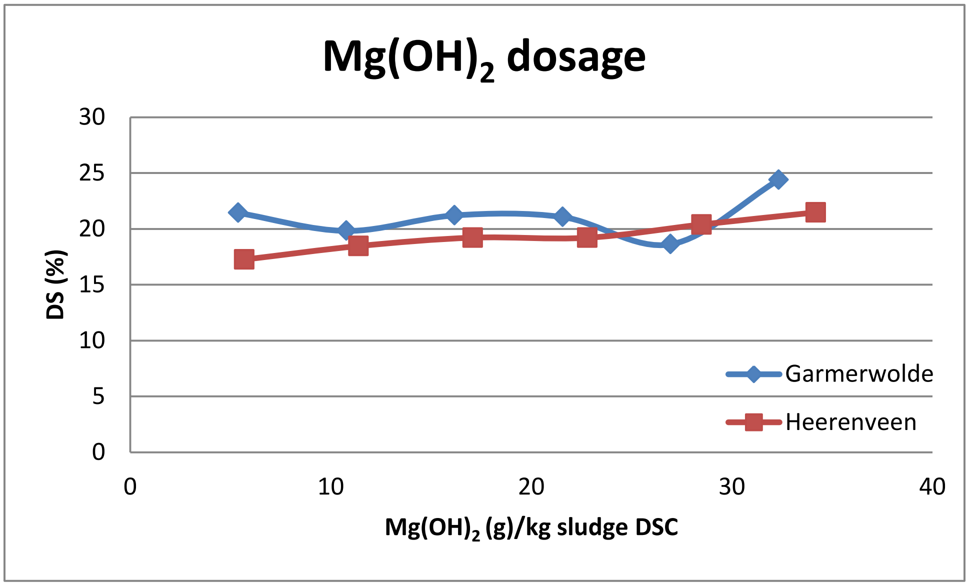

Figure 39 Comparison of DSC using $Mg(OH)_2$ between Garmerwolde and Heerenveen

5.4 Comparison coagulants

The coagulants added, $FeCl_3$, $MgCl_2$ and $Mg(OH)_2$ show different results in dry solid content. We can compare the dry solid contents because there is added the same dosage of PE every time. The dosage of $FeCl_3$ is lower than $MgCl_2$ and $Mg(OH)_2$ but results in a higher dry solid content. The curves of $Mg(OH)_2$ and $MgCl_2$ looks more or less the same. The magnesium will bond with phosphates in the sludge and there will be formed solid struvites. This can be an advantage because the sludge cake will contain less phosphates after dewatering. A disadvantage can be if the struvites settle in pipes and equipment. The expectation is that a higher DSC can be reached if the coagulants with magnesium have more settle time.

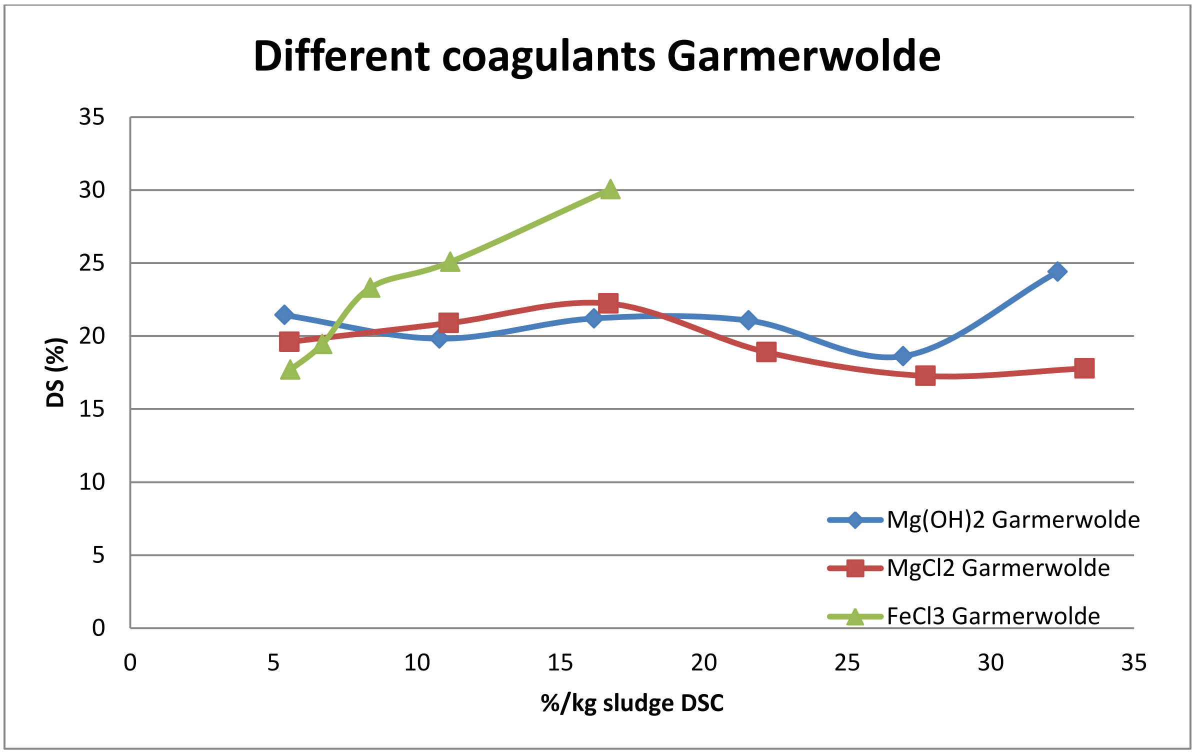

Figure 40 Different coagulants with Garmerwolde sludge

It is clear that there is reached an optimum for the $FeCl_3$ dosage in Heerenveen according to figure 41. There is a significant difference between the DSC of $FeCl_3$ and the DSC of $Mg(OH)_2$ and $MgCl_2$. Further research has to make clear if $FeCl_3$ is indeed the best coagulant or that higher DSC's can be obtained when the settle time increases with magnesium salts as coagulant.

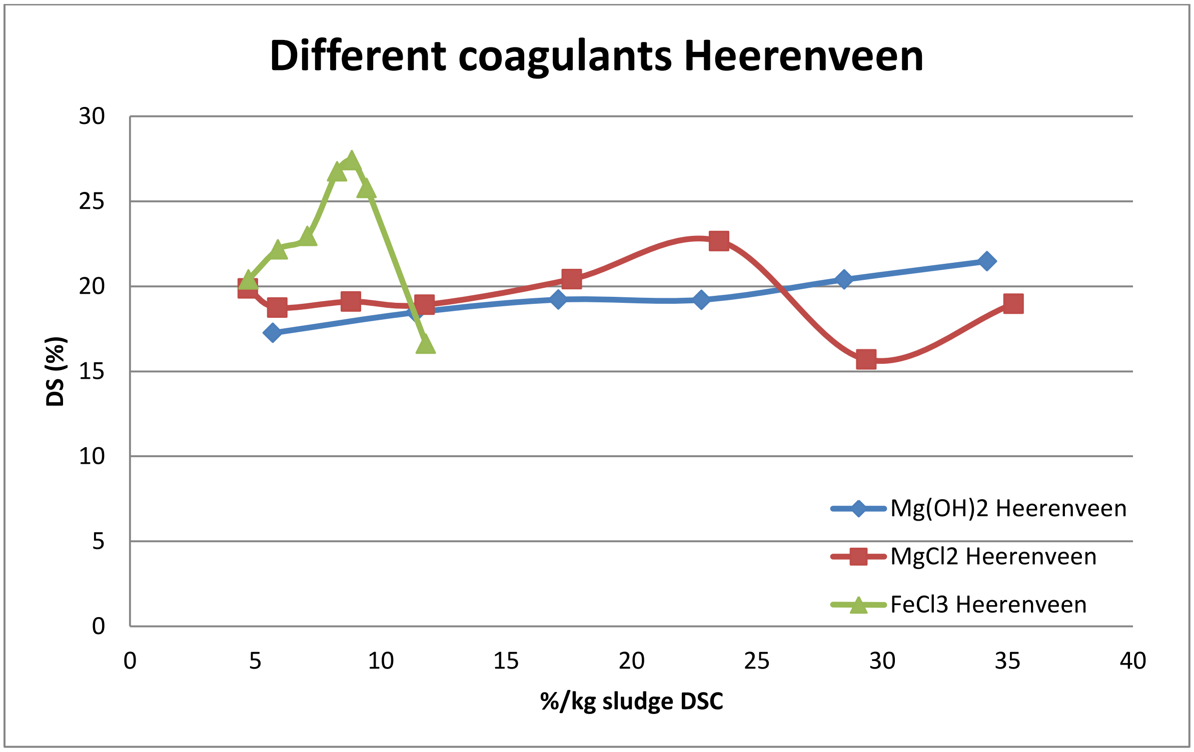

Figure 41 Different coagulants with Heerenveen sludge

6. Design of a coagulant dosing system

6.1 Problem definition

Currently $FeCl_3$ is used as coagulant in both Garmerwolde and Heerenveen. Ferric chloride is toxic and highly corrosive.
In this assignment there is made a design of a dosage system for magnesium hydroxide. Magnesium hydroxide is cheaper than ferric chloride and removes the free phosphates better. Another advantage of magnesium hydroxide is that it does not contain halogens. Desirable is a dosage system that is able to dosage magnesium hydroxide and ferric chloride as well. In this way it is always possible to switch back to the previous system.
Another problem is that the dosage is adapted using subsequent calculation. This means that the dry solid content of the sludge is measured and the dosage on dry solid is calculated after the addition of the coagulant. There is manually taken a sludge sample and the dry solid content is determined in the lab. This is a time-consuming way to calculate the dry solid content and that makes it impossible to reach the optimum coagulant dosage. It is also likely that the dry solid content is not the only parameter that determines the dosage.

Secondly the mixing time and type of mixing are important. The addition of the coagulant is done through a pipeline with a fixed flow and a diameter of 20 mm. The pipe with the coagulant will enter the sludge pipe with a diameter of 150 mm. In Garmerwolde the mixing is done really slow (4 rpm) and the residence time in the mixing buffer varies from 10-50 minutes. In Heerenveen the mixing is done in a sludge buffer with a higher speed (6 rpm) and the residence time is 30-42 minutes. For good mixing it is important that formed flocs will not be demolished due to a too high stirring speed or bad stirring device. The mixing should be homogenous and turbulent. The residence time in the buffers should be long enough to cause floc forming but not so long flocs will be demolished already. The optimum residence time is not determined yet.

6.2 Process description

To optimize the dosage of the coagulant it is important to have a mechanically feedback system or a system that determines the coagulant dosage before adding.

There are some parameters which are probably worth to investigate namely the pH value, conductivity, viscosity and the amount of removed water.
An advantage of a pH, conductivity or viscosity measurement can be that those measurements can be done before adding the coagulant. Further research has to make clear if it is possible to link one of those parameters to the achievable dry solid content of the sludge cake and thereby the dosage of the coagulant.

The measured amount of removed water is directly linked to the dry solid content. However it can be calculate mechanically in contrast with the currently used calculation method for determination of the dry solid before adding chemicals. For now this seems to be the best solution, because the amount of removed water gives already a good indication of the dry solid content. In this design the amount of coagulant is linked to the flow of the mechanical removed water. How higher the dry solid content how higher the flow of the mechanical removed water. There is still a problem with this system because when there is an excess of coagulant, the flow of mechanical removed water can also be high. When there is added too much coagulant there will be formed less flocs and it is possible that there will be removed a big amount of water during the mechanical dewatering step. In this case the water still contains an amount of sludge and the dry solid content of the sludge cake has not reached a desirable value.

Magnesium hydroxide has a longer settle time than ferric chloride and to operate with both of the coagulants it is necessary to add a coagulant aid as well. The flocculation process will go faster in presence of a coagulant aid. In this design polyacrylamide is used as coagulant aid. This coagulant aid is used in combination with metallic coagulants and does not contain halogens.

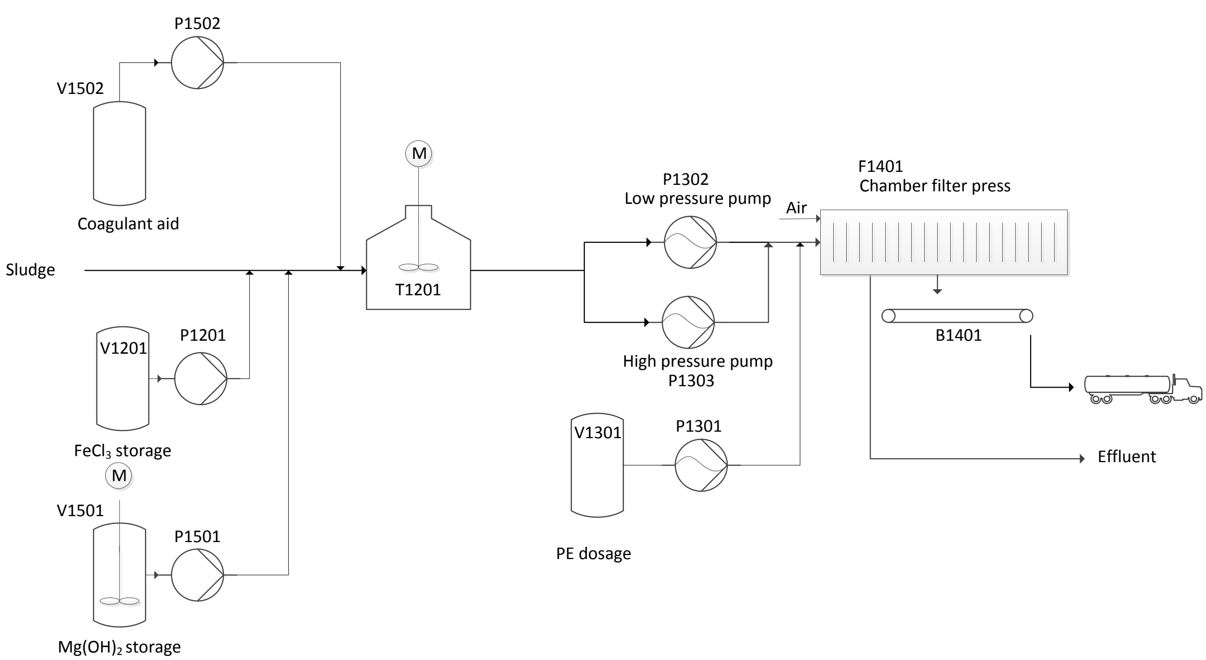

Figure 42 Process flow diagram dosing system design

6.4 Piping and Instrumentation Diagram

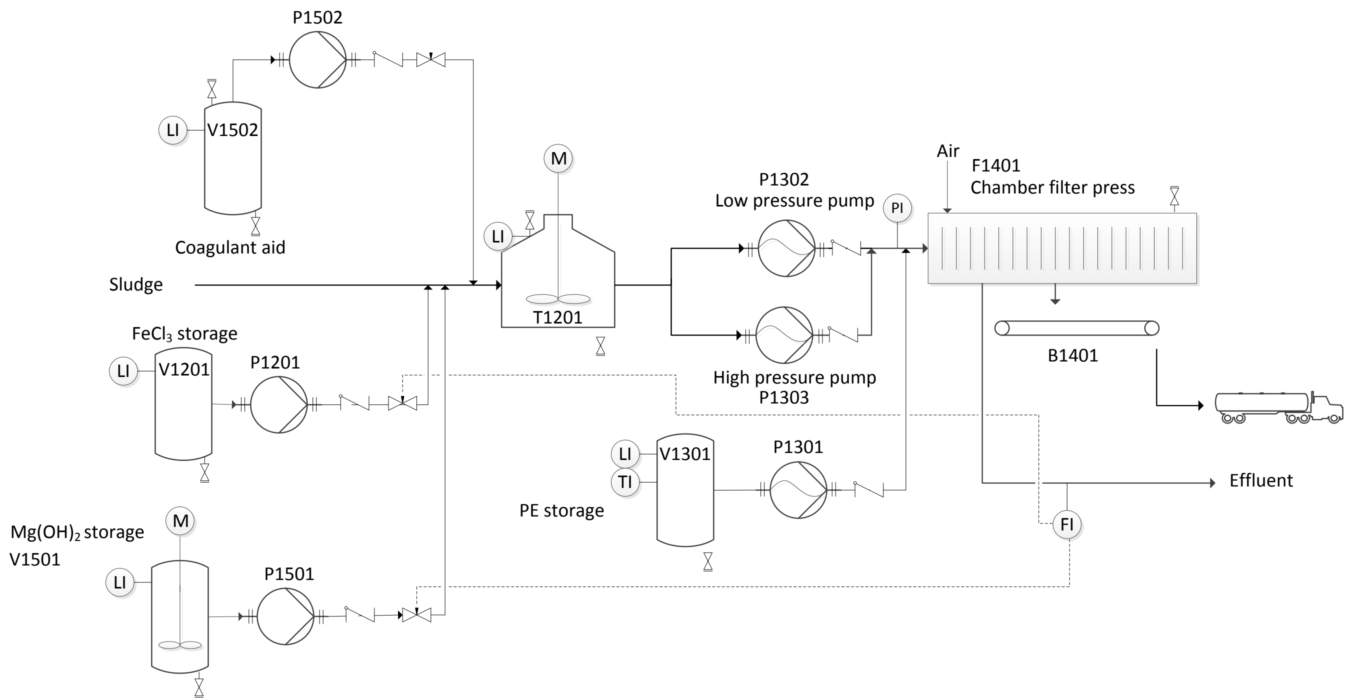

Figure 43 Piping and instrumentation diagram

6.5 Equipment list

4 vessels
3 centrifugal pumps
3 progressing cavity pumps
1 sludge buffer tank
1 chamber filter press
2 mechanical stirrers
1 belt conveyer
5 drains
3 vents
6 check valves
3 needle valves
1 pressure indicator
1 flow indicator

6.6 Process Safety Analysis

In the designed dosing system some safety measures had to be made. The following measures are applied on the dosing system with $Mg(OH)_2$:

- Double amount of pipelines are needed for addition in order that if the dosing system fails or has to be cleaned the dosing can continue.

- Drainage of the sludge line using gravitation. If the system fails, the sludge should not go into the chamber filter presses but into a buffer (for example in the basement).

- The coagulant pipelines should be made of plastic because of the corrosivity of ferric chloride.

-The magnetic hydroxide is stirred to prevent precipitation.

-The storage vessels contain a drain to empty the tank if it is necessary.

-The storage vessels contain a level indicator.

-The storage vessel for the PE contains a temperature indicator to keep the temperature above 20°C.

- Flanges around the pumps in order that it is possible to remove the pump for cleaning or maintenance.

- The coagulant aid tank, the sludge buffer tank and the chamber filter press contain a ventilator, to release air. The ventilator in the chamber filter press is connected to a biofilter to reduce the strong odour.

7. Recommendations

7.1 Recommendation for the WWTP Garmerwolde

$FeCl_3$ turned out to be the best coagulant for the WWTP in Garmerwolde. The highest DSC can probably be obtained when a higher amount than 167.5 g/kg sludge DSC is used. In performed experiments there is obtained an almost linear line with dry solid contents. This amount is that high that it is not preferable for the WWTP because $FeCl_3$ causes relative much chemical sludge. (L. Veltman, 2011)The chloride concentration in the waste water will become too high. The dosage in the plant is now 65 g $FeCl_3$/kg sludge DSC resulting in a DSC of 26%. On lab scale this dosage results in a dry solid content around 20% and is therefore not similar to the WWTP.

7.2 Recommendation for the SDI Heerenveen

$FeCl_3$ also turned out to be the best coagulant for the SDI in Heerenveen. We obtained an optimum for a dosage of 88.5 g $FeCl_3$/kg sludge DSC. In Heerenveen the current dosage of $FeCl_3$ is approximately 60 g $FeCl_3$/kg sludge DSC. We recommend to use a dosage of 88.5 g/kg sludge DSC because in this case the DSC increases with almost 4.5%. It is most likely the costs of the additional needed $FeCl_3$ are less than how much more the sludge cakes will become worth because the energy content will increase.

7.3 Recommendations for plant design

If it is indeed possible to obtain high DSC values with longer settle times with $MgCl_2$ or $Mg(OH)_2$, it could be preferable to use these coagulants. The price of magnesium salts is lower than the price of ferric salts. Secondly the amount of halogens in the waste water will decrease if $Mg(OH)_2$ is used. This is preferable for the environment and will reduce the costs of purification of the effluent. Both plants have to take into account that changing the coagulant will have consequences to the operating system. First the storage in the case of $Mg(OH)_2$ should be changed because this is not a homogenous solution. The storage tank of $Mg(OH)_2$ should be stirred to have a constant dosage because $Mg(OH)_2$ precipitate easily. Probably the dosage of the coagulants has to increase, in comparison to the dosage of $FeCl_3$,to obtain a high dry solid content. If this is the case, there are maybe needed more or larger storage tanks to maintain the same dewatering capacity. It is impossible that the dewatering system is able to switch to a different coagulant at once. Therefore there should be a transitional phase were both $FeCl_3$ and $MgCl_2$ or $Mg(OH)_2$ can be operated at the same time. Such a dosing system can be found in paragraph 6.

7.4 Recommendation for further research

It seems to be that the optimum values of the DSC are not reached yet when $Mg(OH)_2$ is used as coagulant. It is probably possible to achieve higher DSCs when the settle time increases.
We recommend to do experiment with vary settle times in the case of $Mg(OH)_2$.
We also suppose that it is possible to achieve higher DSCs when the settle time increases when $MgCl_2$ is used as coagulant. In both cases it probably takes more time before the coagulation and flocculation is completed comparing with when $FeCl_3$ is used as coagulant.

8. Conclusion

Experiments are done on lab scale with sludge from Garmerwolde and Heerenveen. The goal was to determine important differences between the sludges and coagulants. In appearance the largest difference was the more black colour of Garmerwolde sludge opposite the brown colour of Heerenveen sludge. It was also seen that Heerenveen sludge contained much more pollutions such as twigs and hairs. The odour of Heerenveen sludge was also much stronger. These differences can be explained by the fact that Garmerwolde sludge is digested and the organic material is therefore lower.

The sludge dewatering process in Heerenveen was also closely looked at. The capacity of the installation is 401161 ton sludge a year. The dry solid content of the dried sludge is around 24%. They use $FeCl_3$ as coagulant with a dosage of 58.4 g/kg sludge DS and PE 9048FS as flocculant with a dosage of 7.07 kg/ton sludges DS.

Other differences are found by adding different coagulants and dosages to the sludges. On lab scale the highest DSC can be obtained using $FeCl_3$ as coagulant for both sludges. An optimum dry solid content for Garmerwolde was not reached yet but with a dosage of 167.5 g/kg sludge DSC, a dry solid content of 30% could be reached, is the dosage on lab scale high. Comparing to the WWTP in Garmerwolde, where 65 g/kg sludge DSC is added resulting in 26% DS. Because the difference in achieved DSC is too low, it is not advised to increase the dosage because high dosages of $FeCl_3$ are not preferable. In the case of Heerenveen there was an optimum dry solid content with a dosage of 88.5 g/kg sludge DSC. With this dosage a dry solid content of 27% is obtained.
This DSC is slightly higher than the DSC of SDI of Heerenveen which is 24%. There is expected as well that the same dosage a higher DSC can be obtained in the plant compared with the lab.

The difference between the obtained dry solid contents of the sludge using $FeCl_3$, was interesting to see. With Garmerwolde sludge an optimum was not reached yet, however with Heerenveen sludge high DSC's without increasing the dosage that is used in practice that much.

An improvement of the dry solid content is not acquired with the use of magnesium salts as coagulant. With both sludges it was seen that manually dewatering using a filter, was difficult. There were more flocs formed with $MgCl_2$ but still the water was much more unclear than using $FeCl_3$. Probably the settle time needs to be increased if higher dry solid contents should be reached.

Both sludges require a suitable dosage of coagulant and flocculant. Wrong amounts of coagulant and flocculant cause too large flocs. When the flocs are too thick, the sludge cake will be thicker as well because dewatering is difficult and the filtration resistance will increase.
When the dosage of coagulant and flocculant is too low, it is not possible to obtain a sludge cake at all because of the absence of flocs.

Suggestions for further research are to increase the settle time of the sludge when magnesium salts are added. If magnesium salts prove to be able to reach higher DSC's, it is preferable to use them as coagulants. Mainly magnesium salts are cheaper than ferric salts but secondly if $Mg(OH)_2$ can be used, the contamination of halogens (chlorides) will disappear.

9. Bibliography

Solvay Chemicals. (2006). Retrieved June 2013, from http://www.solvaychemicals.com/Chemicals%20Literature%20Documents/Chlorinated_inorganics/PCH-1610-0001-W-EN_WW_.pdf

A.D. Stickland, C. B. (2008). Fundamental dewatering properties of wastewater treatment sludges from filtration and sedimentation testing. *Chemical Engineering Science*, 5283-5290.

A.J.M. Herwijn, E. L. (1995). *Fundamentele aspekten van slibontwatering, Deel 2: Flocculatiemechanismen.* STOWA.

Bergmans, B. (2011). *Struvite recovery from digested sludge.* Delft: Delft University of Technology.

Coagulants. (n.d.). Retrieved July 2, 2013, from http://www.dgrsol.com/tempWater/municipalWater/drinkingWater/coagulants.php:

Coagulation and flocculation process fundamentals. (n.d.). Retrieved June 24, 2013, from http://www.mrwa.com/OP-Coagulation.pdf

Droste, R. (1997). *Theory and Practice of Water and Wastewater Treatment.* J. Wiley & Sons.

Herwijn, A. (2000). *Het uittesten van de filtratie-expressiecel in de praktijk.* Utrecht: STOWA.

J. Nieuwlands, M. B. (2011). *Trends in slibontwatering.* Amersfoort: STOWA.

Jong, P. d. (1998). *Handboek Slibontwatering.* Utrecht: STOWA.

K.B.Thapa, Y. Q. (2009). Lignite aided dewatering of digested sewage sludge. *Water research*, 623-634.

L. Veltman, H. V. (2011). *Fosfaat terugwining in communale afvalwaterzuiveringssinstalaties.* Amersfoort: STOWA.

P.Fattah, K. (2012). Assessing Struvite Formation Potential at Wastewater Treatment Plants. *International Journal of Environmental Science and Development*.

Pumplocker. (n.d.). Retrieved July 1, 2013, from http://pumplocker.com/images/lit/WEI1/FLUX-HIGH-VISCOSITY-B0000-VISC-CHART-1.PDF

Ravina, L. (1993, april). *Everthing you want to know about Coagulation & Flocculation.* Retrieved June 2013, from www.zeta-meter.com: http://www.zeta-meter.com/coag.pdf

Slump, S. (2013, 5 25). Sludge dewatering Heerenveen. (M. Sveistrup, Interviewer)

Stoffelsma, T. (2012). *Development of a flocculation methology.* Groningen: University of Groningen.

Wetterskipfryslan. (n.d.). Retrieved June 2013, from http://www.wetterskipfryslan.nl/infotype/presspeil/popup_default.asp?ObjectID=2198

10. Appendices

Appendix I: Tables with experimental data.

Table 1: $FeCl_3$ measurements Garmerwolde sludge

ml $FeCl_3$	% DS	% on DS $FeCl_3$	g water after filtering	g water after pressing	g water totally removed	mm thickness
5	17,68	5,58	23,01	31,34	54,35	2,25
6	19,45	6,70	30,99	31,31	62,30	2,25
7,5	23,31	8,38	41,09	27,37	68,46	2,25
10	25,07	11,17	20,10	26,99	47,09	2,25
15	30,06	16,75	36,32	30,93	67,25	2

Table 2: $FeCl_3$ measurements Heerenveen sludge

ml $FeCl_3$	% DS	% on DS $FeCl_3$	g water after filtering	g water after pressing	g water totally removed
4	20,40	4,72	69,23	22,51	91,74
5	22,17	5,90	62,58	25,48	88,07
6	22,95	7,08	49,49	21,52	71,01
7	26,76	8,26	23,35	30,97	54,32
7,5	27,42	8,85	18,42	34,70	53,12
8	25,78	9,45	13,74	27,88	41,61
10	16,62	11,81	0,00	30,49	30,49

Table 3: $MgCl_2$ measurements Garmerwolde sludge

ml $MgCl_2$	% DS	% on DS $MgCl_2$	g water after filtering	g water after pressing	g water totally removed	mm thickness
5	19,60	5,56	60,30	17,48	77,78	-
10	20,88	11,12	81,04	20,80	101,85	-
15	22,23	16,67	82,00	23,66	105,66	-
20	18,90	22,19	84,38	18,44	102,82	5,0
25	17,27	27,74	84,37	17,86	102,23	5,0
30	17,78	33,28	92,64	21,05	113,69	4,5

Table 4: *$MgCl_2$ measurements Heerenveen sludge*

ml $MgCl_2$	% DS	% on DS $MgCl_2$	g water after filtering	g water after pressing	g water totally removed	mm thickness
4	19,88	4,70	70,71	19,84	90,55	-
5	18,75	5,87	79,33	19,14	98,46	-
7,5	19,10	8,81	78,97	22,70	101,67	-
10	18,91	11,75	82,10	17,98	100,08	-
15	20,42	17,62	89,97	20,39	110,35	-
20	22,66	23,50	88,64	18,68	107,32	3,8
25	15,70	29,37	94,76	17,62	112,38	4,5
30	18,98	35,25	100,47	19,11	119,58	4,0

Table 5: $Mg(OH)_2$ measurements Heerenveen sludge

ml $Mg(OH)_2$	% DS	% on DS $Mg(OH)_2$	g water after filtering	g water after pressing	g water totally removed	mm thickness
5	17,26	5,70	72,68	18,34	91,02	5,0
10	18,47	11,40	77,80	21,44	99,24	4,5
15	19,22	17,09	84,65	19,73	104,38	4,0
20	19,21	22,79	90,23	18,80	109,03	4,5
25	20,39	28,49	95,12	19,44	114,56	4,5
30	21,48	34,19	101,18	19,33	120,51	4,3

Table 6: $Mg(OH)_2$ measurements Garmerwolde sludge

ml $Mg(OH)_2$	% DS	% on DS $Mg(OH)_2$	g water after filtering	g water after pressing	g water totally removed	mm thickness
5	21,43	5,39	36,21	28,12	64,33	2,3
10	19,82	10,78	34,26	28,98	63,24	1,9
15	21,21	16,17	38,24	26,73	64,97	2,0
20	21,06	21,56	20,57	32,45	53,02	2,0
25	18,62	26,95	15,79	33,43	49,22	2,1
30	24,40	32,35	20,36	35,92	56,28	1,3

Appendix II: Calculations dosages

To calculate the dosage of the coagulant and flocculant for 100 ml sludge, a calculating scheme can be followed. First it is necessary to know what the dry solid content is of the pure sludge. With this number the amount of dry solid can be calculated in the used amount of sludge. Then de dosage of the coagulant is used. For example when there is used $FeCl_3$, with a dosage of 50 g/kg sludge DSC, there can be calculated how many grams pure $FeCl_3$ should be added. Because there isn't used pure $FeCl_3$ but it is diluted to 4wt% or 40wt%, this should be taken into account. Another important point is the varying density of the different solutions.

Example for the plant conditions in Heerenveen

The dosage of $FeCl_3$ in Heerenveen is 6wt% on dry solid. The dry solid of pure Heerenveen sludge is 3.51wt%. That means that 100 gram sludge contains 3.51 grams of dry solid. In the SDI they use a 40wt% solution of $FeCl_3$.

The density of a 40wt% aqueous $FeCl_3$ solution at 0°C is 1.43 kg/dm^3. This density is used by the mechanics in the SDI in Heerenveen. (Solvay Chemicals, 2006)

Per liter: $1.43 \frac{\text{kg}}{\text{dm}^3} \times 0.40 \text{ dm}^3 = 0.572\ kg$ $FeCl_3$

$FeCl_3$: $\frac{1\ L}{0.572\ kg} = 1.748$ liter $FeCl_3$(40wt%)/kg

Weight of pure $FeCl_3$: $\frac{3.51\ g \times 6wt\%}{100wt\%}$ = 0.211 g

$FeCl_3$ addition in ml: $0.203\ g * 1.748 \frac{ml}{g}$ = 0.368 ml

The amount of PE only depends on the amount of dry solid in the sludge in grams and the dosage of the polymer. In Heerenveen there is added a 0.15 wt% PE solution with a dosage of 7 mg/g sludge DSC. We assume that the density of PE is 1 g/cm^3.

Per liter: $1 \frac{kg}{dm^3}$ * 0.0015 dm^3= 0.0015 kg PE

PE: $\frac{1\ L}{0.0015\ kg} = 666.7$ liter PE (0.15wt%)/kg

Weight of pure PE: $3.51\ g \times 7 \frac{mg}{g}$ = 24.57 mg

PE addition in ml: $\frac{24.57/0.15}{10}$= 16.38 ml

Example for the plant conditions in Garmerwolde

The dosage of $FeCl_3$ in Garmerwolde is 6.5wt% on dry solid. The dry solid of pure Garmerwolde sludge is 3.71wt%. That means that 100 gram sludge contains 3.71 grams of dry solid. In the WWTP they use a 40wt% solution of $FeCl_3$.

The density of a 40wt% aqueous $FeCl_3$ solution at 0°C is 1.43 kg/dm^3. (Solvay Chemicals, 2006)

Per liter: $1.43\,\frac{\text{kg}}{\text{dm}^3} \times 0.40\ \text{dm}^3 = 572\ g$ $FeCl_3$

$FeCl_3$: $\frac{1\ L}{0.572\ kg} = 1.748$ liter $FeCl_3$(40wt%)/kg

Weight of pure $FeCl_3$: $\frac{3.71\ g \times 6.5wt\%}{100wt\%}$ = 0.241 g

Addition in ml: $0.241\ g * 1.748\,\frac{ml}{g}$ = 0.421 ml

The amount of PE only depends on the amount of dry solid in the sludge in grams and the dosage of the polymer. In Garmerwolde there is added a 1 wt% PE solution with a dosage of 7.5 mg/g sludge DSC.

Weight of pure PE: $3.71\ g \times 7.5\ \frac{mg}{g}$= 27.825 mg

PE addition in ml: $\frac{27.825}{10}$ =2.783 ml

Appendix III: Press setup

The sludge goes in the press after filtering the sludge over a Büchner funnel. The press setup consist of a metal ring, a metal disc with holes, two plastic discs, two porous discs, a balance and a mechanical dewatering system which is connected with a computer.

One of the plastic discs is placed on the bottom of the metal ring, the metal disc is placed on top of the plastic disc and there is placed a porous disc on top of the metal disc. The porous disc is covered by a filter paper and 50 grams of sludge is poured over the filter paper. After that the sludge is covered by another filter paper, a porous disc and a plastic disc (see figure 44 and 45). The sludge can now be pressed in the mechanical dewatering system (figure 46). A dense cake is formed if the flocculation and coagulation process was successfully (figure 46).

Figure 44 Press setup

Figure 45 Press

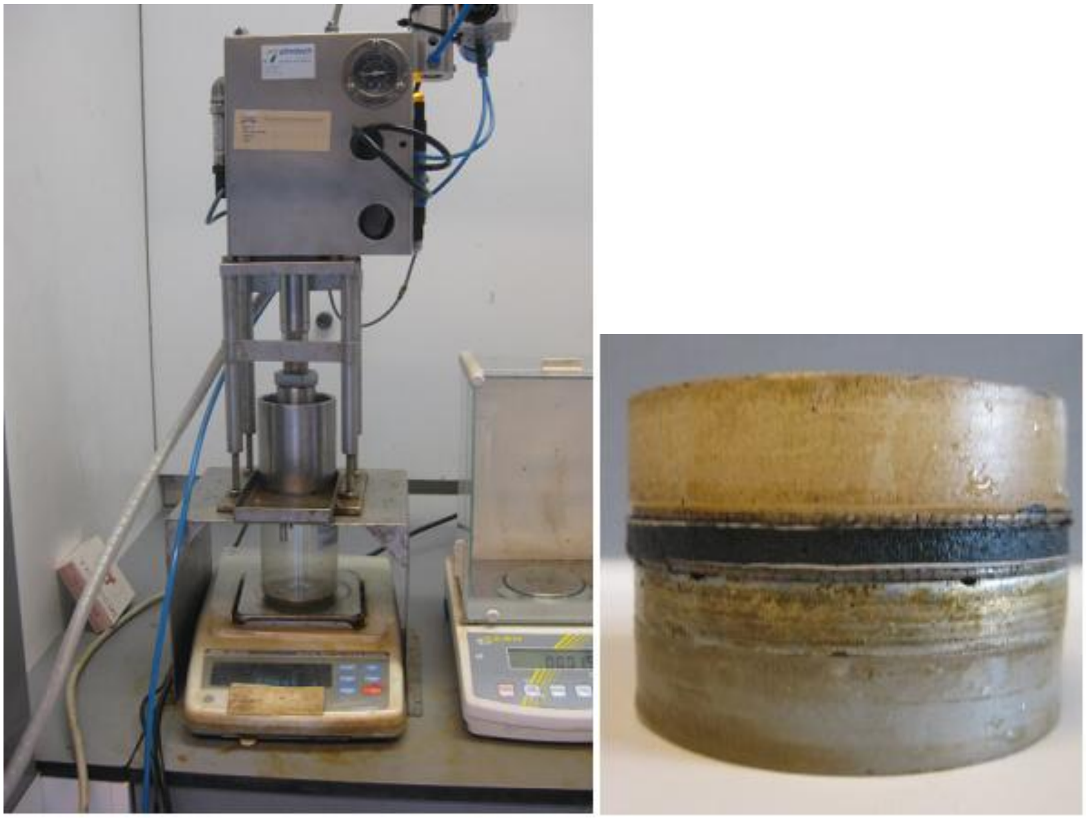

Figure 46 Left: Mechanical dewatering system, Left: Formed sludge cake

The press program of the press setup is reproduced in figure 47. It takes 106.5 seconds to achieve a pressure of 1 bar. It takes 310 seconds to achieve the final pressure of 6.047 bar.

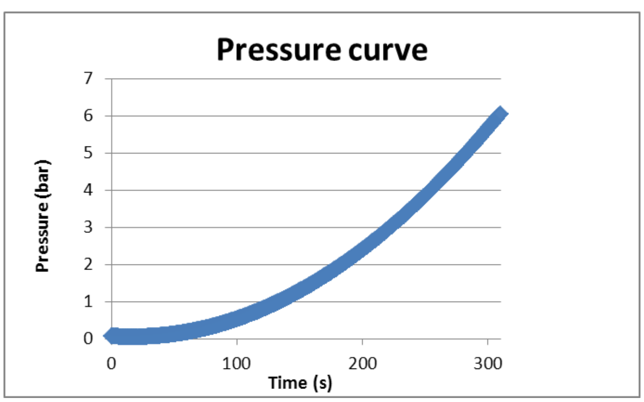

Figure 47 Pressure curve of the press set up

Appendix IV: Dewatering graphs of experiments with Heerenveen sludge

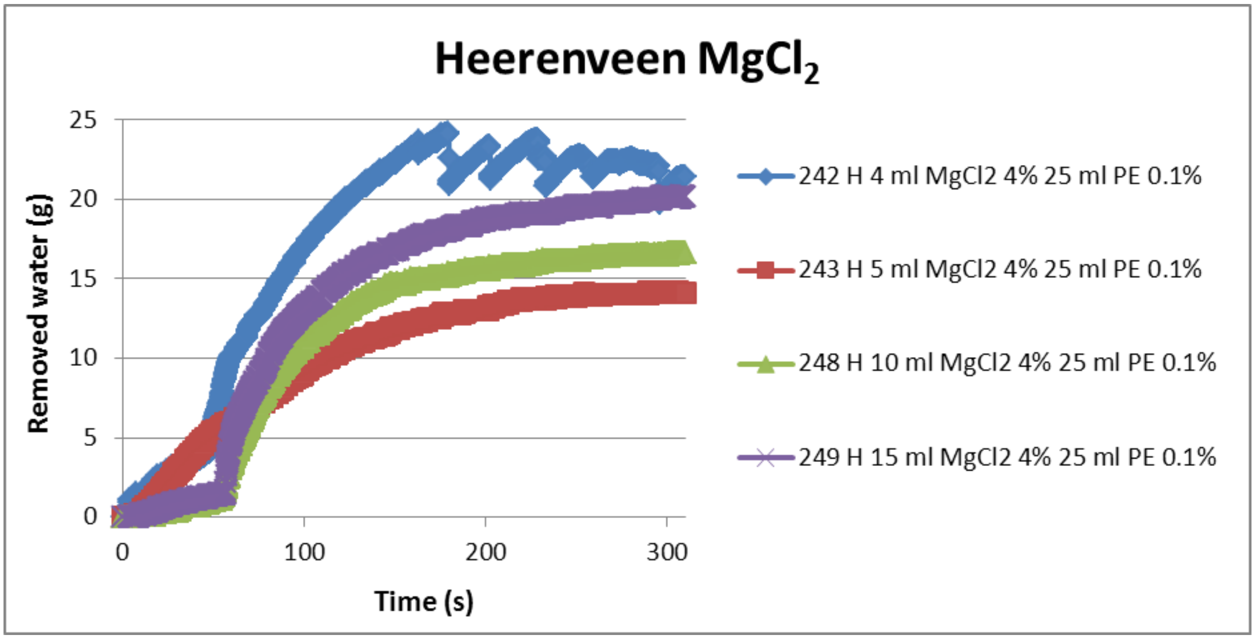

Figure 48 Removed water during mechanical dewatering of Heerenveen sludge with $MgCl_2$

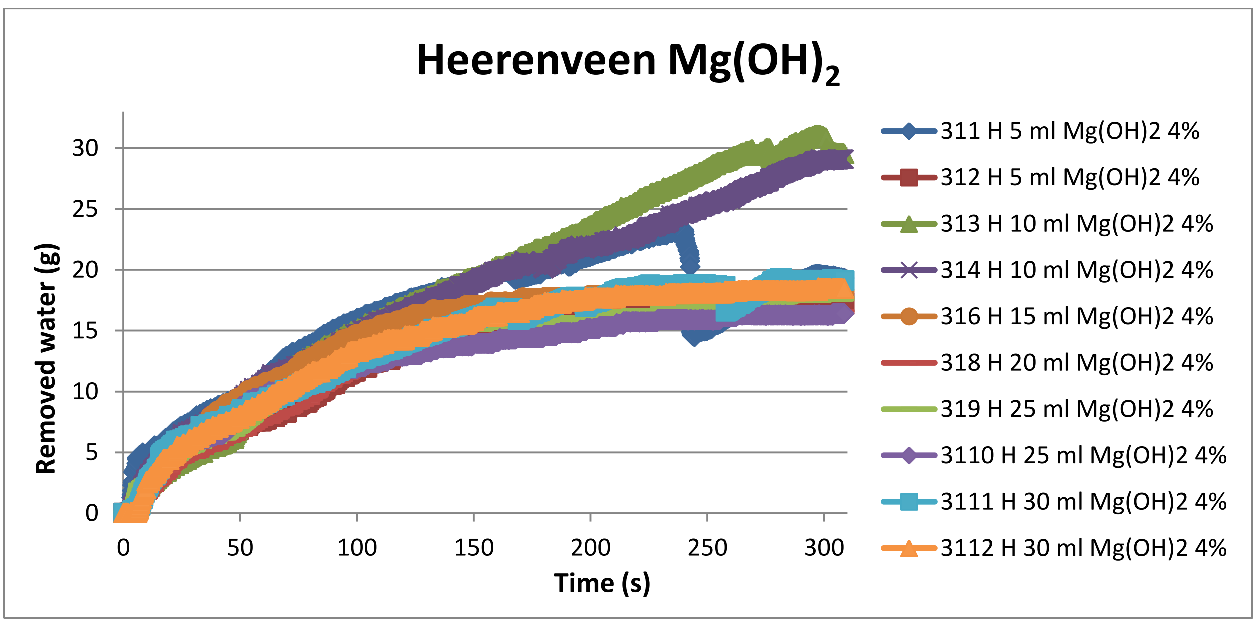

Figure 49 Removed water during mechanical dewatering of Garmerwolde sludge with $Mg(OH)_2$

Appendix V: List of pH values

Because the pH will affect the dewaterability, the pH values are measured of different solutions. The most important differences are between the coagulants. Ferric chloride has the lowest pH, namely 2. Magnesium chloride is also predominantly acidic with a pH of 4 in pure form but in diluted from the pH because higher and is approximately 6. The pH of $Mg(OH)_2$ is almost neutral but slightly basic with a pH of 7.5

$FeCl_3$ 40%	2
$FeCl_3$ 4%	2
$MgCl_2$ 32%	4
$MgCl_2$ 4%	6
$Mg(OH)_2$ 4%	7.5
PE 1%	5.5
PE 0.1%	6.5
Sludge Garmerwolde	7.5
Sludge Heerenveen	7
Sludge GW 10% + 10 ml 8% $MgCl_2$ + 30 ml 0.1 % PE	7
Filtrate GW 10% + 10 ml 8% $MgCl_2$ + 30 ml 0.1 % PE	7.5
Sludge GW 100% + 15 ml 4% $MgCl_2$ + 25 ml 0.1% PE	7.5
Filtrate GW 100% + 15 ml 4% $MgCl_2$ + 25 ml 0.1% PE	8

Appendix VI: Densities for Ferric Chloride with different concentrations

Product Characteristics

FERRIC CHLORIDE - DENSITY

PCH-1610-0001

Density of Aqueous Solutions of $FeCl_3$, kg/dm^3

Concentration, kg $FeCl_3$/kg	Temperature, °C								
	0	10	20	30	40	50	60	80	100
0,01	1,009	1,008	1,007	1,005	1,001	0,997	0,992	0,981	0,970
0,04	1,036	1,034	1,033	1,031	1,028	1,024	1,019	1,008	1,002
0,08	1,072	1,069	1,068	1,066	1,064	1,060	1,055	1,044	1,039
0,10	1,090	1,088	1,086	1,084	1,082	1,078	1,074	1,062	1,057
0,12	1,109	1,106	1,105	1,103	1,101	1,097	1,092	1,081	1,074
0,16	1,147	1,145	1,143	1,141	1,138	1,135	1,130	1,119	1,108
0,20	1,187	1,185	1,183	1,181	1,178	1,174	1,170	1,158	1,142
0,24	1,229	1,227	1,225	1,222	1,219	1,215	1,211	1,199	1,178
0,28	1,274	1,272	1,269	1,265	1,262	1,258	1,254	1,241	1,216
0,30	1,298	1,295	1,292	1,288	1,284	1,280	1,276	1,263	1,237
0,32	1,322	1,319	1,315	1,311	1,307	1,303	1,298	1,285	1,259
0,36	1,373	1,368	1,364	1,360	1,356	1,351	1,345	1,330	1,311
0,40	1,430	1,420	1,415	1,412	1,408	1,402	1,394	1,378	1,376
0,44	1,492	1,475	1,469	1,468	1,464	1,457	1,446	1,427	1,463

__Reference:__ Solvay

FERRIC CHLORIDE - DENSITY

Appendix VII: Properties for Magnesium Chloride with different concentrations

HiTech Fluid Systems
THE BALANCE IS ALWAYS IN THE SERVICE

Properties of Magnesium Chloride Solutions

Weight (%)	Density (kg/m^3)	Cl^- (mg/L)	Mg^{+2} (mg/L)	$MgCL_2$ (kg/m^3)	Water (m^3)	Crystallization Point (°C)	Water Activity
1	1006	7,492	2,568	10.1	0.9962	-0.5	0.995
2	1014	1,506	5,178	20.5	0.9941	-1.1	0.990
3	1023	22,842	7,830	31.3	0.9919	-1.7	0.984
4	1031	30,703	10,524	42.4	0.9897	-2.3	0.978
5	1039	38,696	13,264	53.9	0.9874	-3.0	0.972
6	1048	46,814	16,047	65.7	0.9850	-4.3	0.964
7	1056	55,060	18,873	80.0	0.9825	-5.4	0.957
8	1065	63,444	21,747	90.5	0.9799	-5.8	0.948
9	1074	71,957	24,665	10.5	0.9772	-6.8	0.939
10	1083	80,608	27,631	116.9	0.9744	-7.7	0.929
12	1101	98,329	33,705	145.0	0.9685	-9.7	0.906
14	1119	116,635	39,980	174.8	0.9623	-14.5	0.879
16	1137	135,477	46,439	206.4	0.9552	-18.8	0.848
18	1155	154,838	53,075	239.7	0.9474	-25.0	0.812
20	1174	174,856	59,937	275.1	0.9394	-33.2	0.772
22	1194	195,553	67,031	312.8	0.9312	-28.1	0.727
24	1214	216,940	74,362	352.9	0.9226	-24.3	0.677
26	1235	239,006	81,926	395.4	0.9136	-20.5	0.624
28	1256	261,748	89,722	440.3	0.9039	-17.1	0.567
30	1276	285,091	97,723	487.6	0.8934	-16.4	0.507

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Appendix VIII: Viscosity chart

Viscosity Chart

Media	Viscosity	Temperature
Alkyd resins	500–3.000 mPas (cP)	20 °C
Apple-purée	1.500 mPas (cP)	20 °C
Baby food	1.400 mPas (cP)	40 °C
Brewers's yeast	370 mPas (cP)	20 °C
Butter	30.000 mPas (cP)	40 °C
Butter cream, sour	550 mPas (cP)	20 °C
Butter fat	45 mPas (cP)	40 °C
Castor oil	2.420 mPas (cP)	10 °C
Castor oil	1.000–1.500 mPas (cP)	20 °C
Caustic soda 50%	45 mPas (cP)	20 °C
Chocolate confectionery	2.600 mPas (cP)	40 °C
Chocolate sauce	280 mPas (cP)	50 °C
Cleaning emulsions	1.500 mPas (cP)	70 °C
Cocoa butter	50 mPas (cP)	60 °C
Cocoa paste	4.000 mPas (cP)	20 °C
Coconut oil	80 mPas (cP)	20 °C
Cod-liver oil	35 mPas (cP)	40 °C
Corn oil	30 mPas (cP)	60 °C
Cotton seed oil	60 mPas (cP)	20 °C
Cream, 30–50% fat	11–115 mPas (cP)	20 °C
Dental adhesive	30.000 mPas (cP)	20 °C
Dipropyleneglycol	107 mPas (cP)	20 °C
Evaporated milk	80 mPas (cP)	40 °C
Evaporated milk, sweetened	6.100 mPas (cP)	20 °C
Fruit juice	50 mPas (cP)	20 °C
Fruit juice concentrate	1.500 mPas (cP)	20 °C
Fruit mash	600 mPas (cP)	20 °C
Gelatine	1.200 mPas (cP)	45 °C
Glucose	4.300–6.800 mPas (cP)	25–30 °C
Glycerine 100%	4.500 mPas (cP)	10 °C
Glycerine 100%	1.490 mPas (cP)	20 °C
Glycol	20 mPas (cP)	20 °C
Gravy	110 mPas (cP)	80 °C
Hand creme	8.000 mPas (cP)	20 °C
Honey	2.000 mPas (cP)	40 °C
Jam	8.500 mPas (cP)	20 °C
Lacquers (25% pigments)	3.000 mPas (cP)	20 °C
Lard	65 mPas (cP)	40 °C

Media	Viscosity	Temperature
Molasses 80 °Bx	10.000 mPas (cP)	20 °C
Molasses 83 °Bx	50.000 mPas (cP)	20 °C
Molasses 85 °Bx	100.000 mPas (cP)	20 °C
Motor oil SAE 10W	160 mPas (cP)	20 °C
Motor oil SAE 140	2.300 mPas (cP)	20 °C
Motor oil SAE 20W	160 mPas (cP)	20 °C
Motor oil SAE 30	380 mPas (cP)	20 °C
Motor oil SAE 40	600 mPas (cP)	20 °C
Motor oil SAE 50	900 mPas (cP)	20 °C
Motor oil SAE 5W	50 mPas (cP)	20 °C
Motor oil SAE 90	700 mPas (cP)	20 °C
Oleic acid	40 mPas (cP)	20 °C
Olive oil	85 mPas (cP)	20 °C
Palm oil	130 mPas (cP)	20 °C
Paraffin emulsion	3.000 mPas (cP)	20 °C
Peanut oil	40 mPas (cP)	40 °C
Polyester resin	3.000 mPas (cP)	30 °C
Polyglycerine caprinate	6.000–7.000 mPas (cP)	15 °C
Polymer solution	20.000 mPas (cP)	20 °C
Polyol (A-Component)	85.000 mPas (cP)	10 °C
Polyol, non-pigmented	500–5.000 mPas (cP)	20 °C
Potassium hydroxide	67 mPas (cP)	20 °C
Printing ink (and colours)	550–2.200 mPas (cP)	40 °C
Pudding	1.000 mPas (cP)	40 °C
Rapeseed oil	160 mPas (cP)	20 °C
Resin solution	7.100 mPas (cP)	20 °C
Salad dressing	1.300–2.600 mPas (cP)	20 °C
Salad oil	65 mPas (cP)	20 °C
Shampoo	3.000 mPas (cP)	20 °C
Soft cheese	30.000 mPas (cP)	60 °C
Soybean oil	80 mPas (cP)	20 °C
Soybean oil, treated	600–800 mPas (cP)	20 °C
Starch solution 25° Baumé	300 mPas (cP)	20 °C
Steam turbine oil	300–1.100 mPas (cP)	20 °C
Sugar solution 65° Bx	120 mPas (cP)	20 °C
Sugar solution 70° Bx	400 mPas (cP)	20 °C
Tomato ketchup	1.000 mPas (cP)	30 °C
Tomato paste	195 mPas (cP)	20 °C

Appendix IX: Basis of design

DESIGN BASIS FOR	INFORMATION **DESIGN BASIS**
Dosing system $Mg(OH)_2$ for sludge dewatering in Heerenveen	*Bachelor Assignment* **Conceptual Engineering**
PROJECT: ***1000***	
Approved: Process Eng. Dept. : RUG Client : *Wetterskip Fryslan*	Date of issue: 24-06-2013 Page 71 of 22

DRAFT

Confidential

Dosing system $Mg(OH)_2$ for sludge dewatering in Heerenveen

Wetterskip Fryslan project no. 1000

By: ***M.J. Sveistrup***

Rev: 0, dated 24-06-2013

TABLE OF CONTENT OF DESIGN BASIS (this is the standard design basis)

Note: In general there will be no attachments available at the start of the conceptual engineering

0. INTRODUCTION

The purpose of this document is to give general guidelines during the conceptual/basic engineering of the so-called *1000 project*. All numbers and values as well as descriptions have been agreed upon between the client and Engineering-company. Therefore this document will form the solid basis for the conceptual/basic engineering to be started. It is the intention of *Wetterskip Fryslan* to investigate the *possibility for a $Mg(OH)_2$ dosing system in the sludge dewatering plant* and to prepare all required documents to support the feasibility study.

1. SCOPE

1.1. Function of the facilities

1.1.1. The function of the facilities designated as the *$Mg(OH)_2$ dosing system is to produce 625 kt/y of sludge cake from sludge and $FeCl_3$/$Mg(OH)_2$ and PE as a feedstock.*

1.1.2. *The $Mg(OH)_2$ dosing system* will be close to the *existing $FeCl_3$ dosing system at Heerenveen in the sludge dewatering plant. Feed will be made available from the waste water treatment plant and external locations. Products will be send to Swiss Combi. Byproducts will be send back to the waste water treatment plant.*

1.1.3. A warehouse will be constructed for the storage of the products. The capacity of this warehouse will be for *32 hours production.*

1.1.4. *Waste water will be send to the process sewer system and from there to the biological pond waste water treatment plant (wwtp).* All waste streams (gas, liquid or solid) should be dealt with in agreement with governmental laws, permit requirement, and corporate requirements and guidelines.
Vent gasses will be routed through a vent gas scrubber. A stack will be installed from which the gasses are sent to atmosphere.

1.1.5. The utilities will be available at battery limits, see also stream summary 1.1.9.

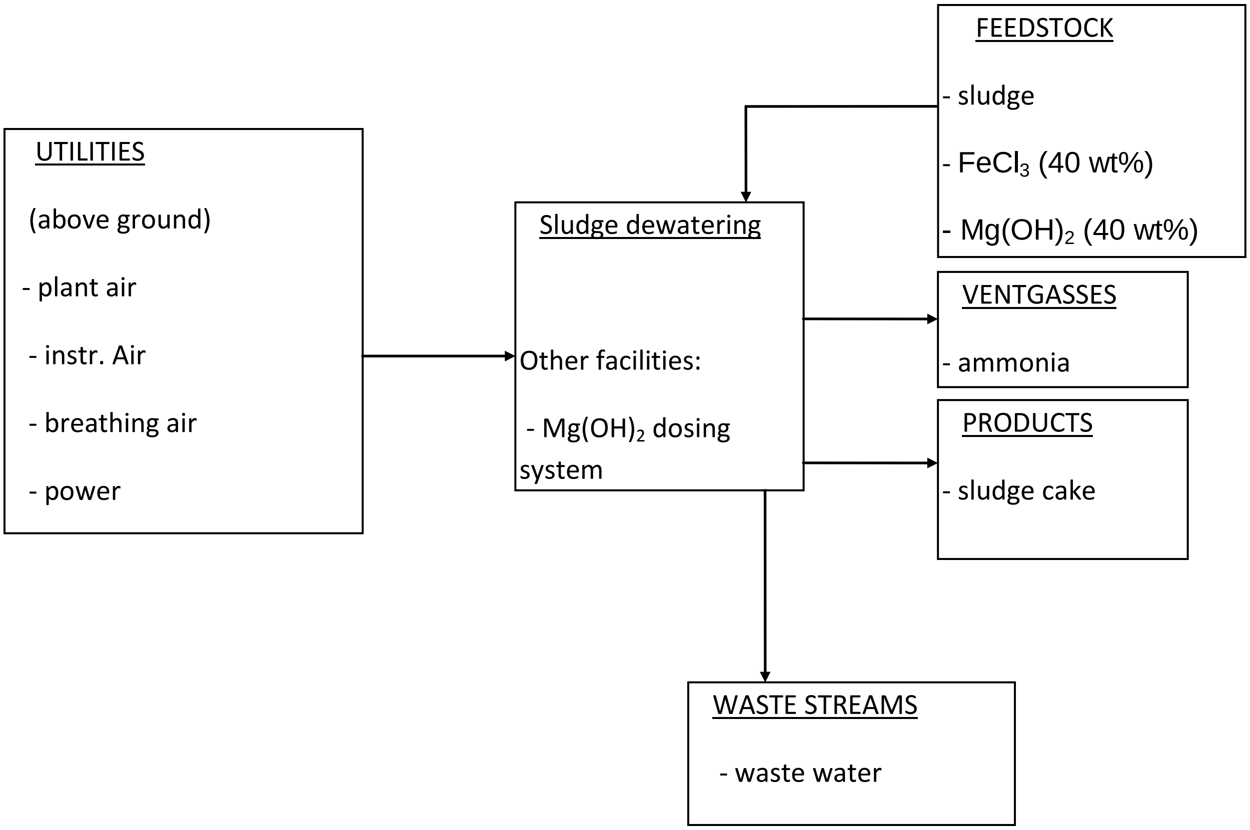
1.1.6. On stream time basis *5840 hours/year*. This leads to a sludge *cake production of 7 t/h.*

1.1.7. **All pressures referred to in this design basis are absolute pressures**.

1.1.8. The facilities of the *$Mg(OH)_2$ dosing system* will be designed with a life time expectancy of 20 years, where possible.

1.1.9 Stream Summary

This will show a sketch (block flow diagram) of all in and outgoing streams). An example of such a sketch is given below.



1.2. Description of the facilities

The plant includes the following sections:
(see also PFD and Process Description in section 6.2)

1.2.1. Tag coding of equipment

Equipment will be tag coded as laid down in *section 6.5*

1.2.2. Production and Utility Facilities

The plant will include the following production sections, this section numbering will form the basis of the PFD's:

Section 1100	*Sludge pre-treatment*
Section 1200	$FeCl_3$ *dosing system*
Section 1300	*PE dosing system*
Section 1400	*Sludge dewatering*
Section 1500	$Mg(OH)_2$ *dosing system*
Section 2100	*Sludge pre-treatment*
Section 2200	$FeCl_3$ *dosing system*
Section 2300	*PE dosing system*
Section 2400	*Sludge dewatering*
Section 2500	$Mg(OH)_2$ *dosing system*

A detailed survey of the utility tie-ins is indicated in the project specifications of the mechanical department.

1.2.3. General facilities

1.2.3.1. Water treating and sewerage

Surface water which can reasonably be expected not to be contaminated shall be collected in a clean water sewer system, which has to be connected to the existing main sewer. (Domestic sewage shall first be treated in a biological pond prior to drainage into the clean water sewer system.) Process water and contaminated surface water shall drain to a process sewer system. And then (via an API-separator) to the biological pond. The maximum allowable temperature of waste water in sewage systems is 30 °C.

1.2.3.2. Bleed, relief and disposal systems

- The relief system has to protect equipment and piping against overpressure, and shall be designed in such a way that the maximum credible relief quantity can be handled, regardless of mode of operation. The system shall be designed in such a way that a release cannot upset the operation of other sections in the plant or adjacent installations.
- Gases containing combustible components which are blown off by safety valves shall be relieved to a flare system or to 'safe location'. Dispersion calculations might be required to determine 'safe location'. A risk assessment study and evaluation will have to be made before the start of the basic engineering. Gases containing non-combustible, non-poisonous or non-odorous components, may be relieved to local vents. The design of these vents must prevent dangerous ground level concentrations of suffocating components (N_2, NH_3, CO_2 etc.) and liquid entrainment. Venting should always be to a safe location.
- Waste gases produced continuously during normal operation and containing significant amounts of combustible, poisonous or odorous components shall be incinerated, or sent to a biofilter.
- For draining of liquids containing combustable, poisonous or odorous components a closed piping system and/or a slop tank shall be installed. Organic liquids not miscible with water are separated and recovered.

1.2.3.3. Control room, social rooms, offices, workshop

The existing facilities of the sludge dewatering plant will be used as much as possible. It is assumed that the plant will have a mixed crew of operators.
The erection or expansion of operator- and social rooms, an office, workshop and additive storage is excluded from the project scope of work. This project will only cover the control room.

1.2.4. Outside battery limit (OSBL)

OSBL connections are detailed in the stream summary 1.1.9.

1.2.5. Safety measures and facilities

All Wetterskip Fryslan and government standards are to be adhered to, see also 2.6.

<u>1.3. Plant site information</u>

The plant will be located in Heerenveen (The Netherlands) on the Wetterskip Fryslan, Wetterwille 4.
The site will be flat and free of obstacles and underground cables.
With regard to earthquakes is referred to Government Building Regulations.
A preliminary report of geotechnical survey will be included in the Project specification of the civil department.
It will be assumed that the soil at the site is not polluted, and that a so called 'Clean soil statement' will be given ('schone grond verklaring').

1.4. Plant capacity and flexibility

The sludge dewatering plant will have a production capacity of 625 kt/y sludge cake, with a composition as given in Paragraph 1.5. See also 1.1.1.

The production of 1000 kg of sludge cake will not require more than 6414 kg of sludge, 14 kg of $FeCl_3$ *and 1.7 kg of PE, based on the normal feedstock specification as per Section 1.6.*

When operating at 80% of design capacity (turn down ratio), the plant shall still be able to produce products which meet their specification as given in Section 1.5 and consumption figures of feedstock and/or utilities as agreed upon and listed above.

1.5. Product specifications

1.5.1. Product sludge cake

Composition:

water/organic material/nitrogen/ammonia/phosphorus/sodiumthiocyanate/phenol/chloride/ferric salts

Battery limits conditions

pressure in bar: 1.01325

temperature in °C: 5, 12, 23

Physical data: physical appearance, solid with a high percentage of water

pH: 7, density: 1279.3 kg/m^3

1.5.2. Co-product filtrate water

Composition: water/nitrogen/ammonia/chloride

Battery limits conditions

pressure in bar: 1.01325

temperature in °C: 5, 12, 23

Physical data: physical appearance, light yellow liquid

pH: 6.5, density: 1000 kg/m^3

1.6. Feedstock specifications at battery limit

1.6.1. Feed sludge

Composition: water/organic material/nitrogen/ammonia/phosphorus/sodiumthiocyanate/phenol

Battery limits conditions

pressure in bar: 1.01325

temperature in °C: -16, 10, 32

Physical data: physical appearance, brown suspension

pH: 7.5, density: 1000 kg/m^3

1.6.2. Feed $FeCl_3$

Composition: 40 wt% $FeCl_3$ in water
Battery limits conditions
pressure in bar: 1.01325
temperature in °C: -10, 12, 25
Physical data: physical appearance, yellow solution
pH: 2, density: 1430 kg/m^3

1.6.3. Feed PE

Composition: 0.15 wt% poly electrolyte in water
Battery limits conditions
pressure in bar: 1.01325
temperature in °C: 18, 20, 40
Physical data: physical appearance, white emulsion
pH: 3.6-4.1, density: 1030 kg/m^3

1.6.4. Feed $Mg(OH)_2$

Composition: 4 wt% $Mg(OH)_2$ in water
Battery limits conditions
pressure in bar: 1.01325
temperature in °C: -10, 12, 25.
Physical data: physical appearance, white emulsion
pH: 7.5, density (pure): 2340 kg/m^3

1.7. Waste stream specifications

1.7.1. Air pollution

Ammonia

The maximum allowable emissions figures are: -
The maximum allowable concentrations are: -
The expected emissions are: 5 $\mu g/m^3$

Remark: The maximum allowable emissions figures and concentrations mentioned here are the figures mentioned in the 'Wet Milieubeheer'.

The emissions include the total of:
- normal and continuous vent and purge losses
- normal leakage from flanges, pumps, valves
- the losses during cleaning and/or repair of equipment

Not included are:
- the expected losses due to blow-off of relief valves
- other losses which are not normal but can be expected (start-up and shut-down losses)

1.7.2. Water pollution

The water flow to the process sewer should be as minimal as feasible. The quantity of organic and inorganic components in the water should be known for normal operating conditions as well as special cases e.g. start-up, shut-down, blow-down and grade change. The temperature is typically 25 °C and shall not exceed 30 °C.

1.7.3. Soil pollution

The soil should be protected to prevent possible pollution. The maximum concentrations in the water that can contaminate the soil are for chloride 200 mg/l, for ammonium 2.5 mg/l and for sulphate 150 mg/l.

1.8. Utility specifications at battery limits

The utility data as well as the statement that the total capacity will be available at Battery Limits will be confirmed and approved by *Wetterskip Fryslan* Utility department. All utility figures mentioned in this chapter shall be verified and adapted if necessary and have to be approved by the Utility Supplier and the client.

1.8.1. Electric power

Reference to be made to Project Specification PS 3.5-(project number) (see PEM 40.20.20 page 4). For preliminary Conceptual engineering, the following information can be used.

STANDARDIZED VOLTAGE
Alternating current: 50 Hz

1.8.1.1. 10,000 VOLT - 3 PHASE - 50 CYCLES

Derived from the utilities system outside battery limits. The system is or shall be neutral grounded by an 8 Ohm resistance. The maximum short circuit level may be 250 up to 500 MVA. For motors above 400 kW.

1.8.1.2. 690/400 VOLT - 3 PHASE + NEUTRAL - 50 CYCLES

This system shall be derived from the 10 kV system with delta-star (DYn) connected transformers. The secondary starpoint of the feeding transformers shall be solidly grounded in the low voltage main switchboard.

<u>690 V main switchboard:</u>

motors from 55 kW with a maximum power (in kW) equal to 17 % of the rated power of one transformer feeder (in kVA).

<u>690 V MCC:</u>

motors from 15 kW up to and including 90 kW.

1.8.1.3. 400/230 VOLT - 3 PH + NEUTRAL - 50 CYCLES

This system shall be derived from the 10 kV or 690 V system with DYn-connected transformers. The secondary starpoint of the feeding transformers shall be solidly grounded in the low voltage main switchboard.

400 V main switchboard:

motors from 55 kW with a maximum power (in kW) equal to 17 % of the rated power of one transformer feeder (in kVA).

To a combined main switchboard/MCC all motors up to the above mentioned maximum power may be connected.

400 V MCC:

motors up to and including 55 kW.

In case of variable speed drives, different power ratings can apply for the connection to the switchboards. Proposals have to be discussed with owner.

The motor of a drive and the motor of the spare-drive, e.g. the A and B drive, shall be connected to different sides of the buscoupler or to different MCC's fed from different sides of the buscoupler. All motors which belong to a specific unit, for instance motors and the auxiliary motors of a compressor, shall be connected to one and the same side of the HV and/or LV buscoupler(s) and/or to one and the same MCC.

1.8.1.4. 230 VOLT - 2 WIRE - SINGLE PHASE - 50 CYCLES

This system is derived from a 400 Volt - 3 phase - 4 wire system having the neutral grounded.

1.8.1.5. 42 VOLT - 2 WIRE - SINGLE PHASE - 50 CYCLES

This system is normally derived from local installed 230/42 Volt 100 VA transformers.

1.8.2. Electric Power - Direct Current

1.8.2.1. 110 VOLT DC - non earthed system

This system shall be derived from the 400/230 V system by rectifier(s) and shall have a battery back-up.

1.8.2.2. 110 VOLT DC - earthed system

This system shall be derived from the 400/230 V system by rectifier(s) and shall have a battery back-up. The +pole of the system shall be earthed in the first 110 V DC switchboard.

1.8.2.3. 24 VOLT DC - non-earthed system

This system shall be derived from the 400/230 V system by rectifier(s) and shall have a battery back-up.

1.8.2.4. 24 VOLT DC - earthed system

This system shall be derived from the 400/230 V system by rectifier(s) and shall have a battery back-up. The -pole of the system shall be earthed in the first 24 V DC switchboard

1.8.2.5. Other voltage systems and networks

Other voltage systems and networks can be used for special instruments (e.g. computer systems). This will be subject to owners approval. These voltages shall always be derived from the 400/230 V system by means of transformers or -in case of DC- rectifier(s) with suitable battery back-up.

Equipment other than motors shall be connected to the different voltage systems as mentioned here-under:

- heater	: 400V or 690V 3 phases
- packaged units	: 400V or 690V 3 phases
- welding socket outlets	: 400V 3 pH
- heat tracing	: 230V
- lighting	: 230V
- socket outlets	: 230V
- computer systems	: 230V
- socket outlets or handlamps and portable tools in enclosed spaces	: 42V
- control of HV switchgear	: 110V DC non-earthed
- control of LV switchgear	: 110V DC earthed
- emergency lighting in control room and switch room	: 110V DC earthed
- network annunciator systems in switch room	: 110V DC earthed
- telephone system	: 60V DC
- process control equipment	: according to EP 5.6-2.1

1.8.3. Water

1.8.3.1. Canal water

The effluent from the waste water treatment installation is discharged in the *Nieuw Heerenveens Kanaal.*

pressure (at ground level)	average	: 7.5	bar
	max. and design	: 16	bar
	minimum	: 6	bar
temperature	average	: 14	°C
	max. and design	: 25	°C
	minimum	: -16	°C

1.8.3.2. Fire fighting water

See canal water. In case of fire the pressure will be boosted up to 16 bar, which is the design pressure of the system.

1.8.4. Air

1.8.4.1. Instrument air

Pressure min. : 4.5 bar
max. and design : 8 bar (setpoint PSV)
norm. : 5.8 bar
Temperature norm. : ambient
design : 50 °C
dew point : -30 °C OR -40 °C
quality : free of oil and dust
A filter shall be installed ISBL.

1.8.4.2. Plant & Breathing air

Pressure min. : 5.5 bar for plant air
: 4.5 bar for breathing air
max. and design : 8 bar (setpoint PSV)
norm. : 5.5 bar
Temperature norm. : ambient
design : 50 °C
dew point : ambient
An ISBL filter for breathing air will be installed.

2. DESIGN CRITERIA AND POLICIES

2.1. Design consideration

- The plant shall be designed as a commercial unit for the performance as listed in 1.1.1.
- Where possible inherently safe design shall be applied.
- Where possible the design shall have a minimum impact on the environment and shall be as energy efficient as possible.
- Establish project key criteria and objectives.
- Establish design life time of the total installations and/or individual pieces of equipment.
- Determine which process parameters should be defined, taken into account the limitations of the technologies selected.
- Asses the significance of the process parameters.
- Identify the basic design parameters (key process parameters).
- Assure that the requirements of all key parties (operation, maintenance, marketing, finance, management, safety, quality) are recognised and presented so as to facilitate priorisation and resolution of conflicts.
- Mention the design criteria references and assumptions (test results, R & D reports, licence package etc.).
- All relevant design criteria of each piece of equipment have to be motivated in a separate document (e.g. Design Condition Analysis).

2.1.1. State of the art of the technologies and process

- The plant and equipment design shall, where possible, incorporate only those modern (state of the art), available and proven technologies that are consistent with highly reliable, low SHE (safety, health, environmental) risk plant design and with the Corporate Requirements and Guidelines.
- The technologies shall be evaluated with 'state of the art' knowledge from inside and outside *Wetterskip Fryslan*. The benchmarking position shall be indicated with an approximate technical/economical evaluation of the considered process.
- Any contractor is expected to consider recent developments of the technologies during design and consult Engineering-Stamicarbon before these are incorporated or rejected.
- The implications of the technologies on equipment design and selection shall be assessed.

2.1.2. Operational requirements

- During process engineering the operating procedures are translated into process design. Operating philosophy must be defined before basic engineering to assure that the designed plant can be operated according to these instructions.
- The degree of atomisation and controlling of the plant is determined by the operating philosophy. Atomisation and control system choice should lead to minimum manning.
- Main and by-product logistics (storage, transport etc.), interference with other plants; off-spec routing shall be indicated.
- Indicate the auxiliary requirements (catalyst, inhibitors, etc.) including handling aspects.

- Operational flexibility shall be assessed in accordance with ideas of the client.
- The installation has to meet the highest performance criteria during transitions: for instance feed composition changes, throughput variations, start up and shut down.
- The design shall be based on maximum and minimum operating conditions including, start up, shut down and cleaning or maintenance procedures, unless otherwise is specified.
- Specify required regeneration equipment (catalyst, adsorbent regeneration etc).

2.1.3. Maintenance requirements

- The specific maintenance philosophy shall be determined by client and Engineering-Stamicarbon.
- The plant equipment and materials of construction shall be consistent with a high service factor and low maintenance cost.
- Preventive, predictive maintenance and regular revision and maintenance intervals should be taken into account.
- The plant design shall allow carrying out as much routine maintenance as possible during operation or during downtime inherently necessary for process reasons.

2.1.4. Allowances for future extension and/or product upgrading

- Allowances for future extension and installation of equipment for product upgrading and off spec routing have to be determined in consultance with client.
- In case of constructing an additional line, the plot-plan of the first line must be designed in such a way that operation of the lines gives synergistic effects.
- In production plants with expected future expansion the capacity of special equipment may be over-designed. This shall be mentioned in the Design Basis and determined by the client.

2.1.5. Project and Technological risks

- The following major technological and project risks and uncertainties are present during the conceptual engineering phase of this project: (kinetics, powder characteristics and thermodynamics partly unknown etc etc.)
- The investigation of risk reduction options and remedial actions are part of this project.
- Indicate with sensivity analysis the economics of the considered risk options.
- After approval of the owner, the contractor is allowed to use other technologies than mentioned in the design.
- Experiences of Wetterskip Fryslan with vendors are reflected in the preferred vendor-list.
- Appreciation's of client can also determine the choice between several alternatives.
- The choice between a commercially proven, pilot plant proven, and a recently developed technology is complex and shall be assessed and agreed by Engineering-Stamicarbon and client.

2.1.6. Equipment including package units

Package units are equipment and/or process systems, which are purchased from specialised vendors in order to obtain the necessary performance integrity.
Package units include:

- Pumps, compressors, blowers, centrifuges, mixers, extruders, granulators and other rotating equipment
- Cooling towers, refrigeration equipment, cooling belts
- All fired equipment, incinerators and flares, hot oil furnaces
- Solid handling equipment including storage, filters, sieves, pneumatic transport, dosing units
- Hoisting equipment, bagging, debagging and packing equipment

Design, manufacturing and erection of package units shall comply with:

- Dutch national and local codes
- International design standards and specifications
- Additional requirements as mentioned in owners dedicated project specifications
- Additional requirements according to owners standard specifications as mentioned in the dedicated project specifications
- The *Wetterskip Fryslan* Corporate Requirements and Guidelines and Operational Requirements.

Equipment, lines, valves etc. shall be designed according to ANSI/DIN specifications where possible.

The scope of supply shall at least include the design, manufacturing, delivery and, when applicable, erection of equipment and or parts, necessary to achieve the required duty and safe operations.

The contractor remains fully responsible for a good design and the fitness for successful operation of the equipment and package units. The contractor remains also fully responsible for delivery in time of documents, services and materials.

In principle, only equipment, components and constructions, which have been proven during at least two years successful operation in similar process conditions, are acceptable.

The contractor makes sure, that at least the following guarantees (by Vendor) are incorporated in the agreements with Vendors:

- The compliance of the units, the components and the performance of the installation with the applicable technical specifications.
- That the installation and its individual parts function properly in all respects and that they are free from defects and sound in terms of design, workmanship and fabrication.
- Specific performance guarantees with regard to consumptions, capacities and quality of products; these specific performance guarantees shall be described as detailed as possible in figures which are easily measurable in the installation while operating.

In principle the Owner will provide a 'Vendor list'. The contractor is allowed to add other vendors to the list, resulting in the 'proposed Vendor list'. The Owner has the right to make modifications to this list. After Owner's approval, the modified/approved Vendor list will be appointed as the 'project Vendor list'. In case no Vendor list is provided by the Owner, the contractor shall compose and provide a 'project Vendor list'. The Owner has the right to make modifications to this list.

2.2. Total Quality Management Aspects

The contractor shall demonstrate that its organisation is supported by a Quality System, which preferably meets the requirements mentioned in ISO9001, in order to achieve quality of engineering. The organisation and procedures of the contractor can be assessed by means of a quality audit. This audit gives information about the deviations between ISO9001 and the contractor's activities. The contractor shall prepare a project quality plan to demonstrate that engineering is executed according to ISO9001. This plan is to be regarded as the translation of the quality system in working procedures during the project. The same applies in rough outlines for the construction phase.

The contractor shall demonstrate a SHE project plan according *to Wetterskip Fryslan* and government standards and requirements.

2.3. Design standards and codes

The facility shall be designed in accordance with:

- *Wetterskip Fryslan* -design specifications and Process Design Guides (if applicable) as defined in the Project specification have to be used.
- Recommended practices as laid down in API reports and bulletins shall be adhered to.
- For the design or rating of shell and tube heat exchangers, the design methods of HTRI, or on contractors request HTFS, are strongly recommended.
- For heat exchanger types different from shell and tube, the design methods of HTFS are recommended or the design methods of approved vendors.
- For the design of fractionators the design methods of FRI are strongly recommended or for specific types of packing or tray types, the design methods of approved vendors.
- For the earthing of equipment the LP3 or LP4 safety measures shall be taken, in compliance with NEN1014.

2.4. Plant availability and sparing policies

2.4.1. Availability

The plant shall be designed for an annual availability of 5840 hours (7 tons per h) on-stream time. Availability should be read as availability for starting, stopping, production and regular cleaning procedures (e.g. Cleaning in Place). While the planned shut-down of the whole plant for maintenance and 'Stoomwezen' inspection might take place every 2 years for 1-2 weeks, the unexpected plant outages may add up to approximately 20 days per year. Regular maintenance or inspection shall not entail the total shut-down of the plant. It should be noted that the plant gets its feed directly from the waste water treatment plant, a shutdown of the latter will generate a shutdown of the subject plant. This effect has been taken into account in the annual availability.

2.4.2. Sparing policy

2.4.2.1. Vital services

Vital services are those which in the event of failure could cause an unsafe condition of the installation, jeopardising life and/or equipment. Running equipment in vital service shall be 100 % spared with one of the power sources being electric drive whilst the other motive source should be steam, diesel or gas turbine. The spare equipment shall always be available for operation and therefore a third facility should be available to allow essential maintenance to be carried out while the plant remains on stream. Vital services will include:

- Safeguarding devices (XPV's) for S1 situations
- Pressure relief systems (two PSV's when must be cleaned after use)
- Instrument air supply (ring line)
- Firewater supply (ring line)
- Electrical supply to control room
- Electrical supply to instruments being part of S1 safety loop

Note: In general there will not be installed two pressure relieving devices, the second being a back-up for the first. However this is required when it is expected that the relief valve will not re-open easily after closure, this may be caused by a sticky product. A second relieving device may be dictated by risk analysis.

2.4.2.2. Essential services

The essential services are those which, in the event of their failure, would result in the plant not being available to operate at 100% capacity and make it impossible to obtain the required availability between planned shut-downs.

Normal running equipment in essential service shall be 100 % spared. The spare unit driver does not require an alternative power source. If more than one piece of equipment, say n units, are required to obtain 100% design capacity, n+1 units shall be installed.

- It may be agreed upon not to install a second pump, but have a complete spare pump and spare motor in stock. This can be done when it is guaranteed that the change can be made in a couple of hours.

Other equipment in essential service shall have adequate provision to ensure operation in accordance with the above definition.

- In some cases, however, i.e. sparing of expensive equipment, the economics may be overriding in sparing policy decisions. (e.g. extruders, compressors)

Essential services include:

- Boiler feed water treating and steam generation facilities
- Seal oil/Lube oil systems of major equipment
- Effluent treatment facilities
- All process unit feed, reflux and product pumps

- Fuelgas supply
- Cooling water supply

2.4.2.3. Non-essential services :
Non-essential services are those which, in the event of failure for a limited time, would not impair production. Rotating equipment in non-essential service need not be spared. Non-essential equipment shall not have provisions for performing essential services.

2.5. Legal requirements and company requirements

The complete list of legal requirements applicable to this project will be defined in the Project specification. It will include requirements derived from the following laws:
- ‘Wet Milieubeheer’ (Environmental Protection Law)
- ‘Stoomwet’ (Rules for Pressure Vessels)
- ‘Arbeidsomstandighedenwet’ (Occupation Safety and Hazard Act)
- ‘Wet verontreiniging oppervlaktewateren’ (Water pollution Act)
- ‘Bouwvergunning’ (Building Permit)

Policies of *Wetterskip Fryslan* management:
- Corporate Requirements and Guidelines and Operational Requirements
- ‘Beleidsverklaring’ (*Wetterskip Fryslan* Policy Statement)

2.6. Safety, health and environmental considerations

Careful consideration must be given to operability and safety under normal operation, turn down, start up, shutdown and emergency conditions.

2.6.1. Corporate Standards

Translate the Corporate Safety and Environmental policies into key design features. Anticipation of the likely Safety, Health and Environment (SHE) restrictions of the permit and *Wetterskip Fryslan* corporate standards is made in the process design. *Wetterskip Fryslan* requirements are among others the Corporate Requirements and Guidelines.

The major potential hazards will be identified using the following methods:
- Systematic process safety analysis (PSA: ‘Process Safety Analysis’) (Proces Veiligheids Analyse)).
- MCA analyses (Max. Credible Accident) to be based on plot plan, lay out and site.
- Risk analyses, effect calculations and damage calculations.
- Standard for dust prevention in the plastics industry NFPA 654-1975, NFPA-68.
- VDI directive for dust explosion.
- DOW F&E Index

The following design standards are to be met:
- Process Design Guide 3.1 "Pressure relieving devices" latest revision.
- For venting requirements, fire protection, evaporation losses, protection against ignitions (several sources), personal protection and design see relevant API-recommendations.

Designing for external fire condition shall be determined by mutual agreement between Engineering-Stamicarbon and owner. According to Corporate Requirements and Guidelines and API-reports all equipment shall be protected against overpressure i.e. also caused by external fire. However indiscriminately designing for external fire conditions has to be avoided by:
Thorough analysis of the cause and the source of the fire. Calculations must be made if the maximum pressure increase, due to external fire, may exceed the design pressure regarding the amount of burning component present.

The contractor shall establish the scope and standard in co-operation with Wetterskip Fryslan for:
* drain systems
* fire protection
* fire proofing, insulation and/or coating
* emergency showers, eye showers

2.6.2. Asbestos
Asbestos or composites containing asbestos will not be used in this plant.

2.6.3. Noise
The maximum allowable noise level of individual pieces of equipment shall be according to DIN 80 dB(A) at 1 meter distance, under all circumstances. However a noise level of less than 75 dB(A) at 1 meter is strongly preferred. The total noise level shall not exceed the so called site noise 'Contours'.

2.6.4. Energy conservation
- Energy and thermal integration aspects should be considered in relation with corporate philosophy and client standpoint or view.
- Pinch Analysis and Exergy Analysis might be applied to check the energy efficiency.

2.7. Process control philosophy

- For the key process parameters (only 5 to 10) 'Statistical Process Control' (SPC) must be applied when agreed upon with the client.
- DCS, model based process control, advanced process control systems should be assessed with regard to process optimisation, environmental pollution and product quality.
- Local panel, centralised or decentralised control of the plant must be considered.
- In an early design phase (feasibility/conceptual) the control philosophy should be regarded in respect with efficiency, quality and Safety, Health and Environmental requirements.

2.8. Overdesign factors

In the design of process-equipment, uncertainty factors in thermodynamic properties, design correlations and calculation methods are historically compensated for by 'overdesign factors'.
Overdesign should be used with caution, the use of indiscriminative arbitrary safety factors should be avoided.

The magnitude of the risk and consequences involved in a certain application will be reflected in the value of the appropriate safety factor. The justification of the overdesign of individual pieces of equipment will be made on the datasheets/duty-specifications.

For the following non critical equipment the overdesign has been agreed upon:

- pumps 10% *(ETC)*
- For several streams in the material balance more than one condition will be shown for 'normal operation', and for 'design conditions'. In this latter balance overdesign factors have been applied on process uncertainties.

2.9. Corrosion allowance

Basically corrosion allowance shall be granted in case of general corrosion attack. For critical process equipment, Engineering-Stamicarbon has to be consulted on this subject. Generally the allowance shall not exceed 3 mm, for economical reasons. A more resistant construction material shall be selected when required, also considering the design lifetime. No corrosion allowance with respect to ambient (atmospheric) conditions shall be used.
All materials to be used for piping and equipment will be detailed in the Construction Material report, which is part of the Conceptual Process Design Package.
The corrosion allowance for utilities (equipment and piping):

instrument air, mat. CS	: 0 (zero) mm
breathing air, mat. galvanised CS	: 0 (zero) mm
plant air, mat. CS	: 0 (zero) mm
nitrogen, mat. CS	: 0 (zero) mm
steam, mat. CS/alloy steel	: 0 (zero) mm
condensate, mat. CS	: 0 (zero) mm
cooling water, mat. CS	: 0 (zero) mm
demineralized water, mat. SS	: 0 (zero) mm

2.10. Economic criteria for optimisation of sub-systems

- An estimate of the production cost and preliminary economic analysis (pay-out time) including sensitivity analysis should be made in co-operation with the client.

For feasibility studies during the design the following prices (in Dutch guilders) will be used:
- (see editions of 'variabele verrekenprijzen Utilities' in order to obtain the prices).

Power : *0,0438* *€/kWh*

2.11. Temperatures and pressures for mechanical design

Regarding temperatures and pressures for mechanical design of plant piping (excluding transmission lines outside battery limits) and equipment, reference is made to the latest revision of Process Design Guide 1.15: 'Determination of the design pressures and design temperatures'. The design conditions will be reported on the Equipment Design Condition Forms which are a part of the Conceptual Process Design Package.

3. GENERAL DESIGN DATA

3.1. Units of measurement

SI units shall be adhered to, and the use of the following specific units is preferred.
- pressure : bar (10^5 N/m^2) absolute pressure unless stated otherwise
- flow : kg/s, kg/h, m^3/s, m^3/h, Nm^3/s
- viscosity : mPa.s
- power and heat flow : Watt (W, kW)
- energy : Joule (J, kJ)
- Nm^3 are defined at 0 °C and 1.01325 bar

3.2. Meteorological data (Heerenveen)

3.2.1. Wind conditions

Prevailing wind : *South West*

3.2.2. Wind speed

- For the design of structures, buildings etc. see the Project Specification.
- For the calculation of heat losses 10 m/s.
- For the calculation of gas dispersion in the atmosphere min. 2 m/s (Pasquill class F) for the MCA calculations.
- Maximal wind speed 16 m/s

- Hour average wind speed 4.7 m/s

3.2.3. Temperatures

In tanks, as caused by the radiation of the sun	: 50 °C
In tanks surrounded by a wall at approximate 2 m	: 60 °C

3.2.4. Air temperatures

Extreme max. dry bulb	: 35 °C
Minimum dry bulb	: -20 °C.

35 °C is exceeded during 10 minutes/year

30 °C is exceeded during 10 hours/year

3.2.5. Design air temperatures for equipment:

- Air compressor	- dry bulb	25 °C	
	- wet bulb	18 °C	
- Air coolers		27 °C	(27 °C is exceeded 39 hours per year)
- Minimum air temperature		*-16 °C*	
- Maximum air temperature		*32 °C*	

- air conditioning : according to HVAC specification.

3.2.6. Relative humidity

Average, summer		*79.5 %*
Design	- summer	*80 %*
	- winter	*100 %*

3.2.7. Barometric pressure

Maximum	1045 mbar
Minimum	975 mbar
Design	1030 mbar

3.2.8. Rain- and snowfall

Rain, maximum 18.7 mm/hour during 60 minutes

Run off: 90 % on paved roads and roofs, 50% on unpaved roads.

Average annual rainfall 735 mm/year.

3.2.9. Environmental conditions

The installations will be erected on Wetterskip Fryslan site at Heerenveen, close to waste water treatment plant and the sludge dewatering plant. The ambient air is polluted with NH_3 , SO_2 , CO_2, nitrate, nitrous vapours and industrial dust. Copper or its alloys shall not be used, unless stated otherwise.