Influence of coal powder and ferric chloride on the dewatering and drying process of sludge

at the WWTP of Garmerwolde

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1 July 2012

Abstract

The WWTP of Garmerwolde treats the waste water produced by the citizens of Groningen. When cleaning polluted water, sludge is produced as a byproduct. In Garmerwolde the sludge is dewatered by a chamber filter press and the resulting sludge cake with a dry solid content of 22.5% is dried by Swiss Combi with the use of natural gas. The resulting granulates are sold to several other companies to be used as fuel. The cost of sludge cake handling is very expensive and makes the price of drinking water higher.

Garmerwolde wants to lower the sludge cake handling cost by the following things:

- By using coal powder in the dewatering process. This will create a sludge cake with a higher dry solid content (around 40%) and therefore Swiss Combi has to remove less water.
- It is suggested that ferric chloride isn't needed anymore when using coal powder. Not using any ferric chloride in the process will reduce the sludge cake handling costs.
- Swiss Combi uses an expensive way of drying the sludge cake by using natural gas. What is the effect on the drying process if coal powder and ferric chloride are used?

In this report the objective is to see whether the above things were indeed a way to improve the dewater ability of the sludge cake and if the sludge cake could be dried by using normal air. The methods used are lab scale experiments to study the effect of coal powder and ferric chloride on the dry solid content of the sludge. The produced sludge cake was then used to obtain sorption isotherms. By measuring sorption isotherms we could see what the effect of different additives (ferric chloride and coal powder) was on the drying process of the sludge cake.

The results of the experiments within this research show that adding coal powder has an positive effect on the dewatering process. Dry solid contents of 40% weren't reached only when using undigested sludge. It was also shown that ferric chloride isn't needed anymore when using coal powder. In the currently setup used at Garmerwolde, a combination of coal powder and ferric chloride gives the best dewatering results. Lastly it was shown by the sorption isotherm experiments the different additives (coal powder and ferric chloride) didn't affect the drying process of sludge.

A higher mass of water per mass of dry sludge is removed, which results in a higher dry solid content of the sludge. Since less water has to been evaporated in the drying process, this positively effects the reduction in costs.

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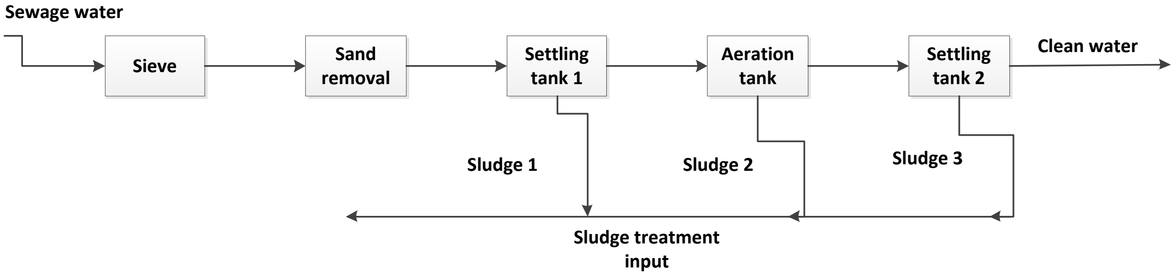
Chapter 1: Introduction

1.1 Introduction[2, 3]

Waste water is created by people due to domestic activities such as using the shower and toilet. This together with rain water is collected in the sewage system and transported to a WWTP. In the region of Groningen, the waste water is treated by the WWTP of Garmerwolde. The WWTP at Garmerwolde is a place where this polluted water is cleaned to be used again. Cleaning polluted water at the WWTP of Garmerwolde involves two major processes. In the first process the sewage water is cleaned. This will create sludge and this sludge is processed in the next step.

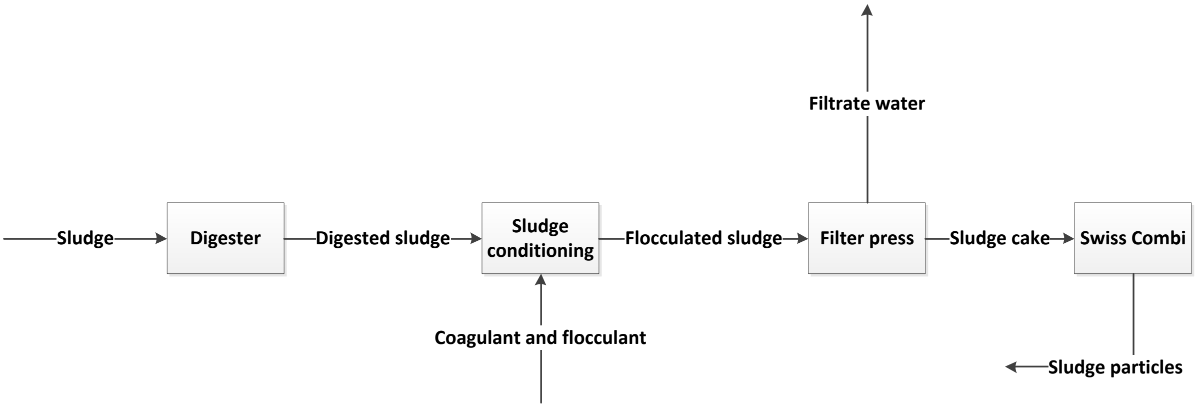
1.2 Waste water treatment at Garmerwolde[2, 3]

Sewage water treatment:



Sewage water will first go to a sieve to remove all large objects, and then sand is removed and picked up by a sand elevator. Thereafter, the waste water is collected in a settling tank. In a settling tank the velocity is so low that particles can settle due to gravitational forces. The settled particles are called primary sludge and are pumped out of the tank. The cleaner surface water from the first settling tank goes to an aeration tank where bacteria are added to the water. The bacteria will use the nutrients and organic compounds in the water and so remove all nitrate and organic pollutants. Sludge from this aeration tank is pumped out and added to the sludge stream. Finally the water will go to a second settling tank, where the last solids and impurities are removed. Clean water from the second settling tank is checked on output concentrations and then ready to be disposed in the local water system. The sludge created in the second settling tank is called secondary sludge and added to the sludge stream.

Sludge treatment:



Sludge created in the sewage water process is first treated in an anaerobic digester. With the use of bacteria this digester produces biogas from sludge. After the digestion, approximately a third of the sludge is converted into biogas. Sludge is collected in a sludge buffer waiting to be dewatered. Before the sludge can be dewatered in a chamber filter press it must be conditioned. Sludge conditioning is decomposed in two steps. First the sludge is mixed with a coagulant namely ferric chloride ($FeCl_3$) which provides coagulation. A solution of 400 grams/ liter is added to the sludge at a dosage of 65 grams/ kg dry sludge. After the coagulation process a polyelectrolyte is added in the piping system. A solution of 20 grams/ liter is added at a dosage of 6-7 grams/ kg dry sludge through a dosage system. By adding polyelectrolyte to the coagulated sludge large flocs are formed which is called flocculation. The coagulation process together with the flocculation process enhances the dewater ability of the sludge. The sludge is then transported to a chamber filter press. In the chamber filter press, high pressures up to 15 bars are used to compress the sludge into sludge cake. The resulting sludge cake has a dry solid content of around 22.5%. Further removal of water is done by Swiss Combi, which thermally treats the sludge cake. Using a drum dryer the dry solid content is increased from 22.5% to 88%-92%. The remaining product is granulate solid with a high energy value.

1.3 Research goals

The objective of this research is to reduce the sludge cake handling costs at the WWTP of Garmerwolde. In this research there are three main questions to investigate:

- The sludge cake produced at Garmerwolde is still too wet. Swiss Combi, the company that dries the sludge cake, has to evaporate a lot water and this very expensive. Will using coal powder in the mechanical dewatering process improve the dry solid content of the sludge cake?
- Ferric chloride is used as a coagulant in the mechanical dewatering process. By eliminating the use of ferric chloride can we achieve the same or higher dry solid contents?
- What is the effect of coal powder and ferric chloride on the drying process? Can the produced sludge cake still be dried sufficiently?

To reach these goals a literature study is done to get insight in the above subjects. Experiments are done to see if we can achieve high dry solid contents when using coal powder and when using coal powder and no ferric chloride. To see if coal powder and ferric chloride affect the way the sludge dries sorption experiments were done to obtain sorption isotherms of the created sludge.

Based on the results of this research, a recommendation is given to improve the sludge cake handling process at the WWTP of Garmerwolde.

Chapter 2: Literature study

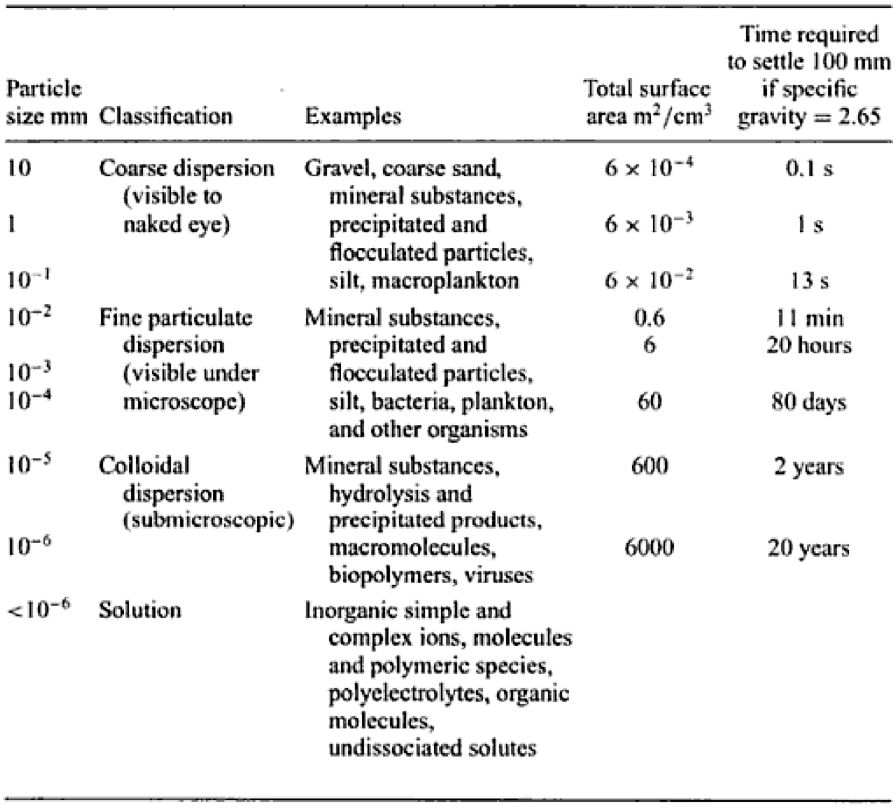
2.1 Introduction

In this chapter, a literature study is performed to gain further understanding in: sludge composition and dewater ability, coagulation and flocculation processes, the use of ferric chloride and the drying of sludge cake.

2.2 Sludge composition[7]

Sludge is a byproduct of wastewater treatments. The sludge from wastewaters consists of water with the domestic and industrial materials you find in the sewers. This sludge, may compromise suspended and/or dissolved organic and/or inorganic matter, bacteria and algae. Much of this suspended material has a microscopic size. Particles that are smaller than 10^{-5}mm are referred to as colloids[6]. Particles of colloidal dimensions are able to retain a dispersed state because of certain characteristics that promote their stability. Stability describes the ability of these particles to maintain a dispersed state. Such characteristics include the surface charge of the colloidal particles and the degree of hydration of the particle. Particles in the colloidal size range requires a lot of time to settle as table 1.1 shows. It is therefore feasible to remove colloidal particles from the waste water by methods other than the force of gravity. A method to remove sludge from waste water is by using high pressure equipment. By using a press, the water content of the sludge is decreased. But still it is difficult to dewater sludge even by high pressures because of the small size and the water content bound to the colloidal particles. Bound water in colloidal particles refers to: water trapped in the cell structure, surface water that is bound by adhesive and adsorptive forces, interstitial water that is bound by capillary forces between sludgeflocs and hydrated water that is chemically bound to the particle. Bound water from the colloidal particles is not easy to remove by mechanical means. Therefore coagulation and flocculation processes, which

Table 1.1 Classification of particle sizes



Particle size mm	Classification	Examples	Total surface area m^2/cm^3	Time required to settle 100 mm if specific gravity = 2.65
10	Coarse dispersion (visible to naked eye)	Gravel, coarse sand, mineral substances, precipitated and flocculated particles, silt, macroplankton	6×10^{-4}	0.1 s
1			6×10^{-3}	1 s
10^{-1}			6×10^{-2}	13 s
10^{-2}	Fine particulate dispersion (visible under microscope)	Mineral substances, precipitated and flocculated particles, silt, bacteria, plankton, and other organisms	0.6	11 min
10^{-3}			6	20 hours
10^{-4}			60	80 days
10^{-5}	Colloidal dispersion (submicroscopic)	Mineral substances, hydrolysis and precipitated products, macromolecules, biopolymers, viruses	600	2 years
10^{-6}			6000	20 years
$<10^{-6}$	Solution	Inorganic simple and complex ions, molecules and polymeric species, polyelectrolytes, organic molecules, undissociated solutes		

are described in the following chapter, are used to make the dewatering process of sludge easier.

2.3 Coagulation and flocculation[1, 5, 9]

2.3.1 Coagulation

Large, heavy particles suspended in water will settle out quite readily, but smaller lighter particles such as in sludge, settle very slowly or, in some cases, not at all. Coagulation consists of treating the water with certain chemicals to bring nonsettable particles together into larger, heavier masses of solid material. These are then easier to remove. Such masses are called “floc”.

Coagulation includes several operations[5]. The first step in the process consists of feeding chemicals to the water. The chemical conditioning changes the properties of the sludge solid, such as its surface charge and particle size. The coagulation is performed by neutralizing the particle surface charge. The Zeta potential is used to indicate the colloidal particle stability. A higher Zeta potential means a greater repulsion force between the colloidal particles and a more stable suspension. A low Zeta potential creates a more unstable system and the colloidal particles tend to aggregate with each other. Thus by lowering the Zeta potential, particles will naturally repel each other and hold the small, colloidal particles apart in suspension. The negative charge on these particles is then reduced, which allows the van der Waals forces to encourage aggregation of colloidal and fine suspended materials to form “microflocs”. Different chemicals may be used in coagulation, depending upon the characteristics of the water and sludge being treated. An important factor for choosing a good coagulant is the pH value of the water. With sufficient alkalinity present in the water to complete the coagulation process, it may be necessary to add alkalinity in the form of soda ash. If coagulation occurs in the acid zone, of pH about 5.0 to 6.0, an acid may be added for proper pH value. The most commonly used coagulant is aluminum sulfate or merely “alum”. Alum is granular powder-like material, which is readily soluble in water and is easily applied as a solution or as a dry material. When conditions are too acid, iron salts such as ferric chloride or ferric sulfate are being used instead of alum. Iron salts are much less expensive then alum but are generally more corrosive and are often difficult to dissolve. Also their use may result in high soluble iron concentrations in the effluent stream.

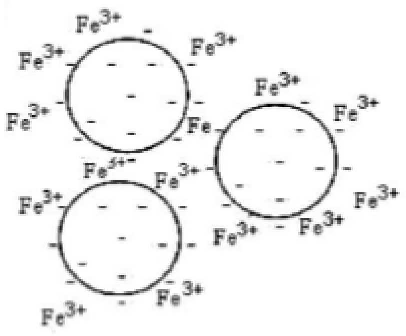


Figure 1: The coagulation is performed by neutralizing the particle surface charge, in this case by Fe^{3+}

2.3.2 Flocculation[9, 10]

The second and final step in the process is flocculation, which refers to gentle agitation of the treated water for a period of time. This favors the collision of the “microflocs” with each other and with the other suspended particles in the water. This causes them to stick together or agglomerate and grow into larger flocs. Van der Waals forces are the biggest contributor to the floc formation. The flocculation process in sludge conditioning is carried out with use of highly molecular weight polyelectrolytes. When mixing utilized through mixing equipment, shear is created and the polymer is dispersed throughout the suspension. There it will form aggregates “flocs” of colloidal particles within the sludge.

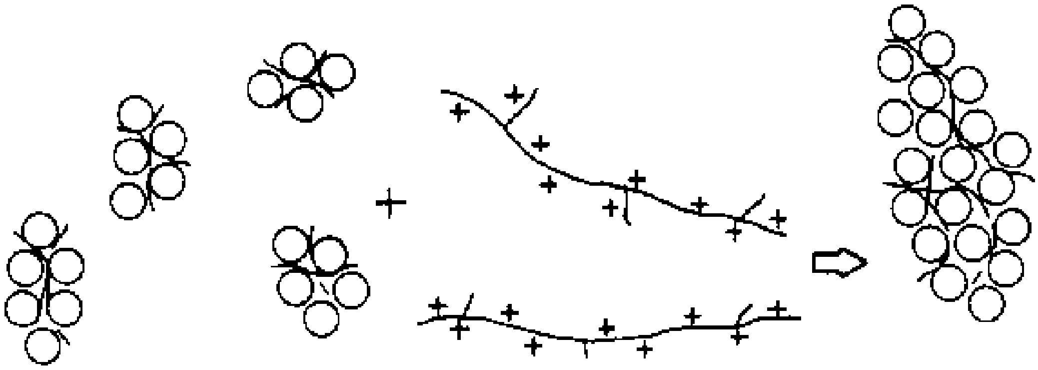


Figure 2: The forming of flocs occurs when polymers with a high charge density adsorb to particles and form large flocs.

The floc size continues to build through additional collisions and interactions with the polyelectrolyte. A higher floc density, which originates when the polyelectrolyte has a high bonding strength with the particles, improves the dewater ability. This is because the water can now move fast through the large voids around the dense flocs. To create large irregular flocs it requires careful attention to the mixing velocity and amount of mixing energy. Creating too much shear through the mixing equipment will cause the flocs to torn apart. And once the flocs are torn apart it is difficult to get them to reform to their optimum seize and strength.

2.4 Ferric chloride

Ferric chloride or iron (III) chloride is a chemical compound that is commercially manufactured in mainly two ways. By the exothermic reaction between ferric oxide and hydrochloric acid:

$$Fe_2O_3(s) + 6\,HCl(l) \rightarrow 3\,H_2O(l) + 2\,FeCl_3(s)$$

Or as a solution from the oxidation of ferrous oxide with chlorine:

$$2FeCl_2(aq) + \; Cl_2(g) \rightarrow 2FeCl_3(aq)$$

In this way it can be immediately used as a coagulant in wastewater treatment. Liquid ferric chloride is a corrosive, dark brown oily-appearing solution. The ferric chloride concentrations of these solutions are mostly in the range of 35%-45%.

Some of the important properties of ferric chloride are listed in table 2.1.

Table 2.1 Properties of anhydrous ferric chloride

Molecular Formula	$FeCl_3$
Molar Mass	162.2 (g/mol)
Appearance	Dark grey to black powder
Melting Point	306°C
Boiling Point	315°C (decomposition temperature)
Density	2.898 g/cm^3
Solubility in water	480 g/L (20°C)

Ferric chloride as coagulant

Ferric chloride reacts[4] in waste water with hydroxide alkalinity to form ferric hydroxide $(Fe(OH_3))$:

$$2\,FeCl_3 \;+\; 3Ca(HCO_3)_2 \rightarrow \;2\,Fe(OH)_3 \;+\; 3\,CaCl_2 \;+\; 6\,CO_2$$

Ferric is a hydrolysis product that possesses high cationic charge. This cationic charge enables ferric hydroxide to neutralize the electrostatic charges on colloidal compounds and bind the negatively charged particles on itself. The ability of ferric hydroxide to bind is the mechanism of forming floc aggregates. The floc aggregates are very dense compared to other sulfate based coagulants. Because of this difference, in plant situations one can expect to use about 30% less ferric chloride than for example aluminum sulfate, to achieve same results.

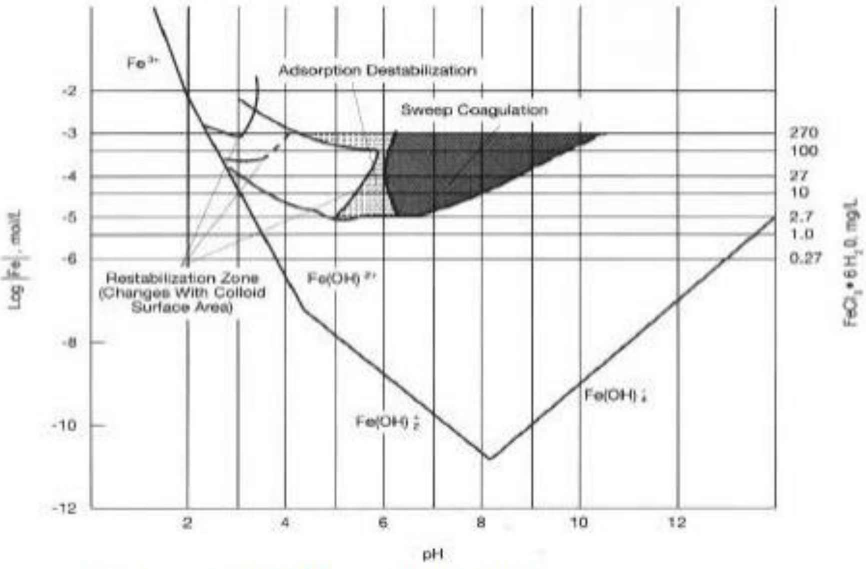


Fig 3: Ferric chloride solubility chart

As stated earlier, the pH of the waste water is an important characteristic of choosing the right coagulant. A major advantage of ferric chloride is that it can be used over a very wide range of pH and compared to other coagulants has a very low solubility. This characteristic is shown in figure 3.

2.5 Drying of sludge[13, 14, 15]

The drying of sludge is the final operation in the sludge handling process, carried out prior to dispatching. Drying refers to the final removal of water, or another solute, and the operation often follows evaporation, filtration or crystallization. In the case of sludge cake, drying is an essential part of the process and is done by Swiss Combi. It is very important that after drying, the sludge cake has very low water content for other companies to be used as fuel. In assessing the efficiency of drying the sludge cake, the effective utilization of the heat supplied is the major consideration.

The moisture content of sludge is expressed in terms of its water content as a percentage of the mass of the dry material. If sludge is exposed to air at a given temperature and humidity, the sludge will either loose or gain water until an equilibrium condition is established. The equilibrium moisture content (EMC) is the moisture content at which the sludge is neither gaining nor losing moisture see figure 4. This EMC varies widely with the moisture content and the temperature of the air. The moisture content (M) of sludge is defined as: $M = \frac{m_s - m_{sod}}{m_{sod}} \times 100$, where m_s is the mass of the sludge with moisture and m_{sod} is the oven-dry mass of sludge. Now the EMC is the moisture content of the sludge for a given temperature and relative humidity. The total moisture content less the equilibrium moisture represents the moisture which can be evaporated by drying in the air in question. This moisture is called “free moisture”. Thus, at a temperature of 20°C, potato as shown in figure 4, in contact with air of 30% humidity retains the same moisture content. Potato holding less moisture will pick up moisture from air with 30% humidity; potato damper than this will lose moisture in such air. It is therefore obvious, that air of 30% humidity cannot dry potato, because this moisture content is in equilibrium with the air.

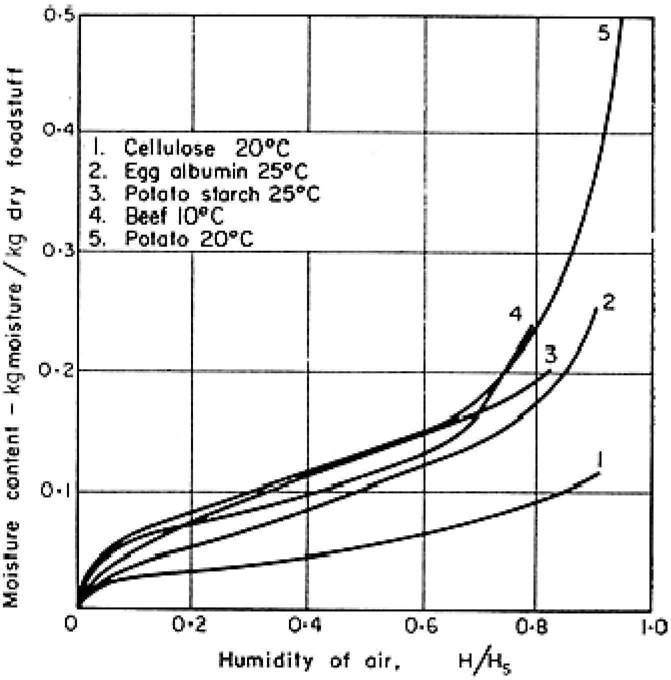


Fig 4: Equilibrium moisture contents

Equilibrium moisture contents are determined by exposing the sludge cake to a constant relative humidity environment[12], created by a saturated solution of a particular salt. This is an especially useful method, because at any temperature, the concentration of a saturated solution is fixed and does not have to be determined. Where the solute is a solid in the pure phase, it is easy to determine that there is indeed saturation. Since a given saturated salt solution provides only one relative humidity at any desired temperature, a different relative humidity must be achieved by selecting another salt.

Chapter 3: Experimental work

3.1 Introduction

The following chapter describes how the dewatering experiments and adsorption experiments are carried out.

3.2 Sludge handling[7]

Sludge is a variable organic product. The content of sludge is influenced by what is offered to the WWTP at a given moment. As a consequence the results of the experiments may differ when using different badges of sludge. Secondly, when storing sludge over time, degradation takes place. This will change the dewater ability of the sludge. Therefore sludge was stored at 5°C and after two weeks disposed. Before starting an experiment the initial dry solid content of a badge of sludge was determined. This was done by weighing a sample and dry it in the oven at 105°C. Thereafter the sample was weighed again to see how much water was evaporated. When doing the dewatering experiments we used a fixed dry solid content of 3%. So for example when the dry solid content was 4.5%, water was used to bring it to 3%.

3.3 Dewatering experiment[7]

This section describes the method to perform the dewatering experiments. Used equipment and the right amount of chemicals are defined in appendix A

An amount of sludge is poured into a beaker and slowly stirred for a half hour to homogenize the settled particles. When using coal powder in the experimental setup, it is also put in the beaker of sludge to homogenize with the sludge. After this, about 100 mL of sludge is poured into another beaker. In this stage we add dependable upon the setup an amount of ferric chloride. We stir it again by hand for another minute. Thereafter dependable on the setup, an amount of polyelectrolyte is added to the sludge and mixed in the mixing equipment for 3 seconds.

The sludge is poured into the filtration cell of the press. This cylinder is first build up with a bottom plate, a metal frame, a porous plate and a paper filter. The sludge is put on this with a filter paper and a porous plate. The cylinder is closed with a plastic top which executes the pressure on the piston.

Now the filtration cell will be placed in the press. The pressing time is 5 minutes with a linear pressure build up from 1 to 6 bars.

After the sludge is pressed, the resulting sludge cake will be weighed. The filter cake will then be dried in an oven at 105°C for 24 hours. Then the sludge cake is weighed again. This way we can calculate the dry solid content of the sludge cake.

3.4 Adsorption experiment

1.) Build the following set-up (figure 3) with a 500 mL beaker and beneath the beaker a saturated salt solution. The sludge sample is put in a petri-dish and placed on top of a piece of PVC-tube. The beaker is sealed off with aluminum foil and tied together with elastic strings so no air can escape.

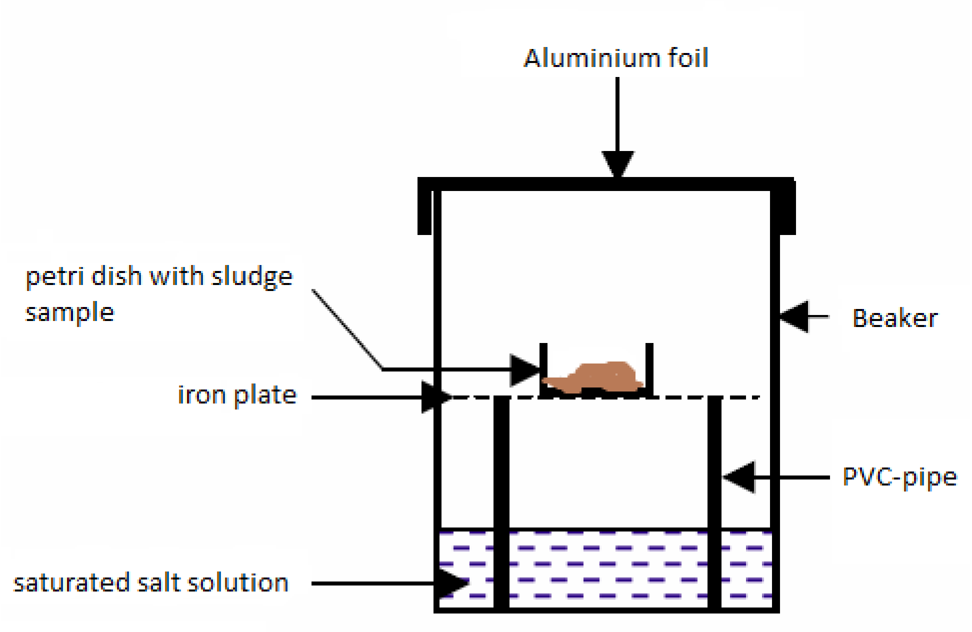


Figure 3

2.) Grind the sludge cakes in a coffee grinder to a fine powder, to create more area so the sludge will better adsorb the moisture. Place approximately 1 gram of sludge powder in a petri dish.

3.) We use four kinds of saturated salt solutions to create four different kinds of humidity. This is illustrated in the following table:

Salt	**Solubility in water (g/L) at 20°C**	**Relative humidity at 20°C (%)**	**Relative humidity at 50°C (%)**	**Relative humidity at 80°C (%)**
Magnesium chloride (MgCl)	543	33.07	30.54	26.05
Sodium bromide (NaBr)	905	59.14	50.93	51.43
Sodium chloride (NaCl)	359	75.47	74.43	76.29
Potassium chloride (KCl)	344	85.11	81.20	78.90

4.) The saturated salt solutions are made in a beaker by stirring the right amount of salt and water. Now the PVC-tube is put in the beaker with on top the petri-dish. Coffer the beaker with aluminum foil and elastic strings and place it in the oven with the right temperature.

5.) After 24 hours remove the beaker out the oven and weigh the sample. The difference in weight is the amount of moisture the dry sample has adsorbed. Now we know the amount of water adsorbed by a fixed temperature and humidity and we can construct a point on a adsorption isotherm diagram.

6.) Repeat this procedure with all saturated salt solutions by the same temperature to collect more points on the adsorption isotherm diagram. Now repeat the procedure using the temperatures in the above table.

3.5 Experimental strategy

First of all experiments were carried out to test the optimum amount of ferric chloride and polyelectrolyte. Also the ideal mixing time and mixing intensity were tested. This was done to see if we could produce typical dewatering results that lead to dry solid contents of 20-25%. Using these conditions and fixed parameters, the influence of adding coal powder and ferric chloride can be investigated on digested and undigested sludge. To do this we carried out the following experiments:

- Digested sludge with ferric chloride
- Digested sludge with ferric chloride and coal powder
- Digested sludge with coal powder
- Undigested sludge with ferric chloride
- Undigested sludge with ferric chloride and coal powder
- Undigested sludge with coal powder

From the sludge cakes that were formed we measured their dry solid content and compared them with each other to see what gives the best dewatering result. The resulting sludge cakes were used to conduct sorption experiments. To see what effect different kinds of humidity had on the sludge samples, we had to create different kinds of humidity[12]. Different kinds of saturated salt solutions in a closed environment with a fixed temperature, gives different kinds of humidity's in that environment. For example a saturated NaCl solution at 20°C gives a humidity of 75%. In this way we could see how much water was adsorbed by the sludge sample in a given amount of time.

Chapter 4: Results and discussion

4.1 Introduction

This chapter describes the results of the dewatering experiments and sorption isotherms. All unprocessed data of these experiments can be found in appendix B and C

4.2 Influence of coal powder and ferric chloride to sludge on dewatering

To investigate the effect of coal powder and ferric chloride on the dewater ability of sludge, coal was added to the sludge in combination with or without ferric chloride. We also looked at the difference between undigested sludge and digested sludge. This experiment consists of six series, which were described in paragraph 3.5. The tests were carried out according to the description in paragraph 3.3.

In series 1, 2 and 3 we tested the effect of coal powder and ferric chloride on undigested sludge, which is a mixture of primary sludge and secondary sludge. Results of these tests are presented in table 4.1, 4.2 and 4.3.

Table 4.1: DSC of undigested sludge with ferric chloride

Experiment	**Ferric chloride (mL)**	**PE (mL)**	**Coal powder (g)**	**DSC (%)**
1	2.8	20	0	30.5
2	2.8	20	0	18.3
3	2.8	20	0	22.4
4	2.8	20	0	31.0
5	2.8	20	0	18.3

We can see in that the DSC of the sludge fluctuates. A possible explanation for this is that it was very hard to see if the sludge formed good flocs. This can account for the low DSC of experiment 2, 3 and 5. It is possible that we stirred too long and the flocs were broken and therefore shows us how important the stirring time is.

Table 4.2: DSC of undigested sludge with coal powder and ferric chloride

Experiment	**Ferric chloride (mL)**	**PE (mL)**	**Coal powder (g)**	**DSC (%)**
1	2.8	20	0.8	27.0
2	2.8	20	0.8	35.8
3	2.8	20	0.8	32.5
4	2.8	20	0.8	26.9
5	2.8	20	0.8	18.2

We can see from table 4.2 that adding coal powder to undigested sludge with ferric chloride, enhances the dewater ability, resulting in higher DSC. But we also see that the DSC just as in table 4.1 fluctuates.

Table 4.3: DSC of undigested sludge with coal powder

Experiment	**Ferric chloride (mL)**	**PE (mL)**	**Coal powder (g)**	**DSC (%)**
1	0	20	0.8	44.9
2	0	20	0.8	44.8
3	0	20	0.8	43.5
4	0	20	0.8	40.3
5	0	20	0.8	44.3

Undigested sludge with coal powder and no ferric chloride gives the best dewatering results. In these experiments the DSC didn't fluctuate very much.

From the first three series we can conclude that undigested sludge gives the best dewatering results and DSC. You would expect that a combination of coal powder and ferric chloride would give the best results. Apparently when using undigested sludge, coagulation isn't an important factor anymore and can be left out. A possible explanation for this is that undigested sludge doesn't contain much destabilized particles[11]. It must also be noted that the results in series 1 and 2 fluctuate. Too come to a more accurate result, more tests should be performed and a better study of the influence of the stirring intensity and stirring time.

In series 4, 5 and 6 we tested the effect of coal powder and ferric chloride on digested sludge. Results of these tests are presented in table 4.4, 4.5 and 4.6.

Table 4.4: DSC of digested sludge with ferric chloride

Experiment	**Ferric chloride (mL)**	**PE (mL)**	**Coal powder (g)**	**DSC (%)**
1	2.8	20	0	12.9
2	2.8	20	0	8.8
3	2.8	20	0	14.5
4	2.8	20	0	12.7
5	2.8	20	0	10.9

The experimental setup used in series 4 is the same as the current situation at Garmerwolde. At the WWTP of Garmerwolde DSC of 22.5% are reached. It is shown from table 4.4 that these DSC are not reached and are much lower. A few possibilities can explain the lower DSC reached in the dewatering experiment:

- We couldn't achieve good floc formation, because the stirring intensity was too low or high.
- We stirred to long, creating too much shear and therefore the flocs were broken.
- We did not use enough PE or ferric chloride.

We can conclude from this, that it was very hard to create the same conditions as at Garmerwolde.

Table 4.5: DSC of digested sludge with coal powder and ferric chloride

Experiment	Ferric chloride (mL)	PE (mL)	Coal powder (g)	DSC (%)
1	2.8	20	0.8	26.7
2	2.8	20	0.8	26.1
3	2.8	20	0.8	27.8
4	2.8	20	0.8	27.5
5	2.8	20	0.8	22.2

Adding coal powder has a positive effect on the dewater ability of digested sludge. DSC of the sludge becomes significantly higher.

Table 4.6: DSC of digested sludge with coal powder

Experiment	Ferric chloride (mL)	PE (mL)	Coal powder (g)	DSC (%)
1	0	20	0.8	17.4
2	0	20	0.8	18.1
3	0	20	0.8	15.8
4	0	20	0.8	15.3
5	0	20	0.8	15.8

Using only coal powder, dewatering results were much better than when only using ferric chloride. We can conclude from the experiments first of all, that we couldn’t create the same DSC as created at the WWTP of Garmerwolde. This is because it is very difficult to create the same conditions in an experimental setup as in real. There a lot of parameters that must be considered during a dewatering experiment: right amount of additives, other equipment, and stirring time and intensity. This all affects the dewatering and eventually the final DSC of sludge cake. Second off all we could clearly see that adding coal powder to sludge enhances the dewater ability en gives higher DSC.

If we compare undigested sludge with digested, we see that undigested sludge in general gives better dewatering results and higher DSC. A possible explanation for this is that primary and secondary sludge, have a low colloidal nature and therefore have better dewatering abilities. In all experiments we see that adding coal powder has a positive effect on the dewatering results.

4.3 Influence of different additives on drying sludge

To investigate what the effect was of different additives on the drying process of digested and undigested sludge cakes, we carried out tests as described in paragraph 3.4. Change in final moisture content was measured, to produce equilibrium moisture diagrams. Unprocessed data of these experiments can be found in the appendix C. Figures 5, 6 and 7 show these equilibrium moisture diagrams with their respective sorption isotherms measured at three temperatures and different humidity's. The results show us that any type of sludge doesn't adsorb much water at any temperature. The moisture content varies between 0.6 and 6.51%. Undigested sludge with ferric chloride and coal powder at a temperature of 20°C adsorbed the most water, but the differences between the sludge samples are very small. A possible explanation is that every sludge sample had the same brittle structure when powdered, and therefore behave the same in adsorbing water. What we also see is that when increasing the temperature, the sludge samples still adsorb roughly the same amount of water. You would expect that when increasing temperature and humidity, the sludge samples would adsorb much more water than they did. Over all we can see that the additives in the sludge don't affect the drying of sludge. Also the undigested and digested sludge give roughly the same sorption isotherms.

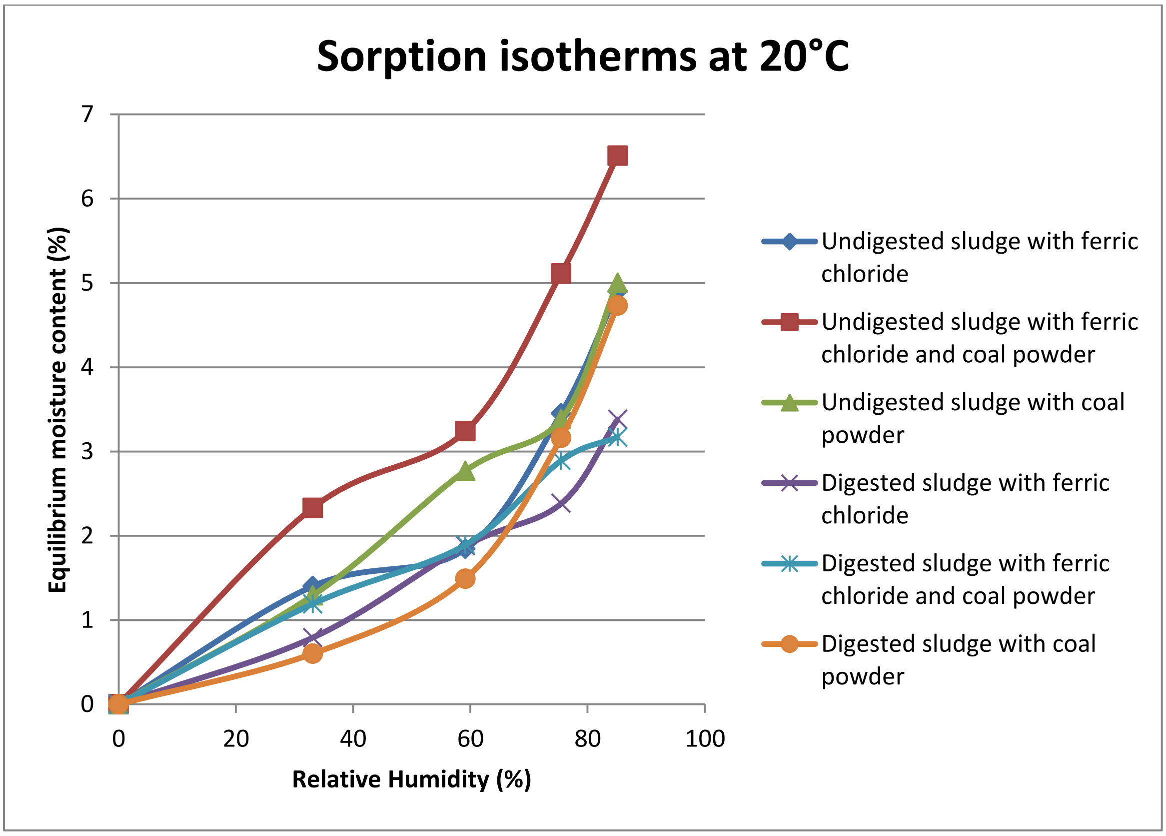


Fig 5: Sorption isotherms at 20°C

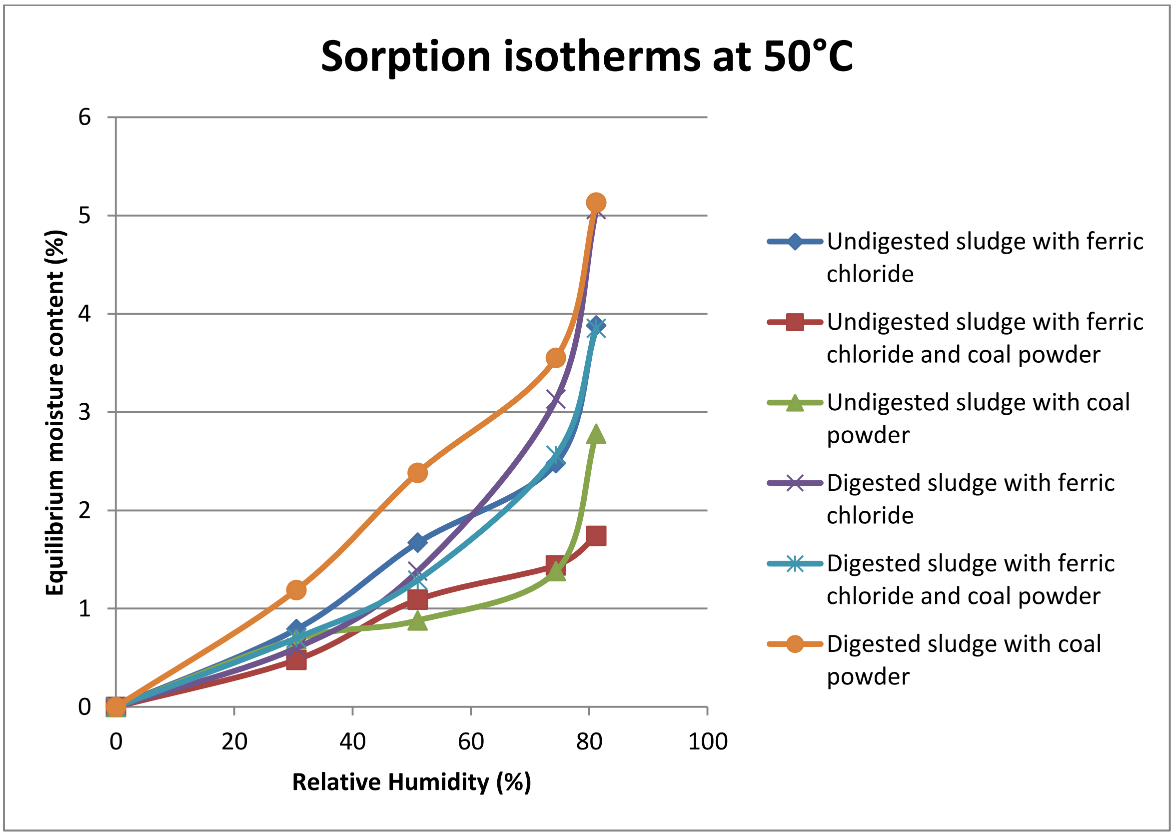


Fig 6: Sorption isotherms at 50°C

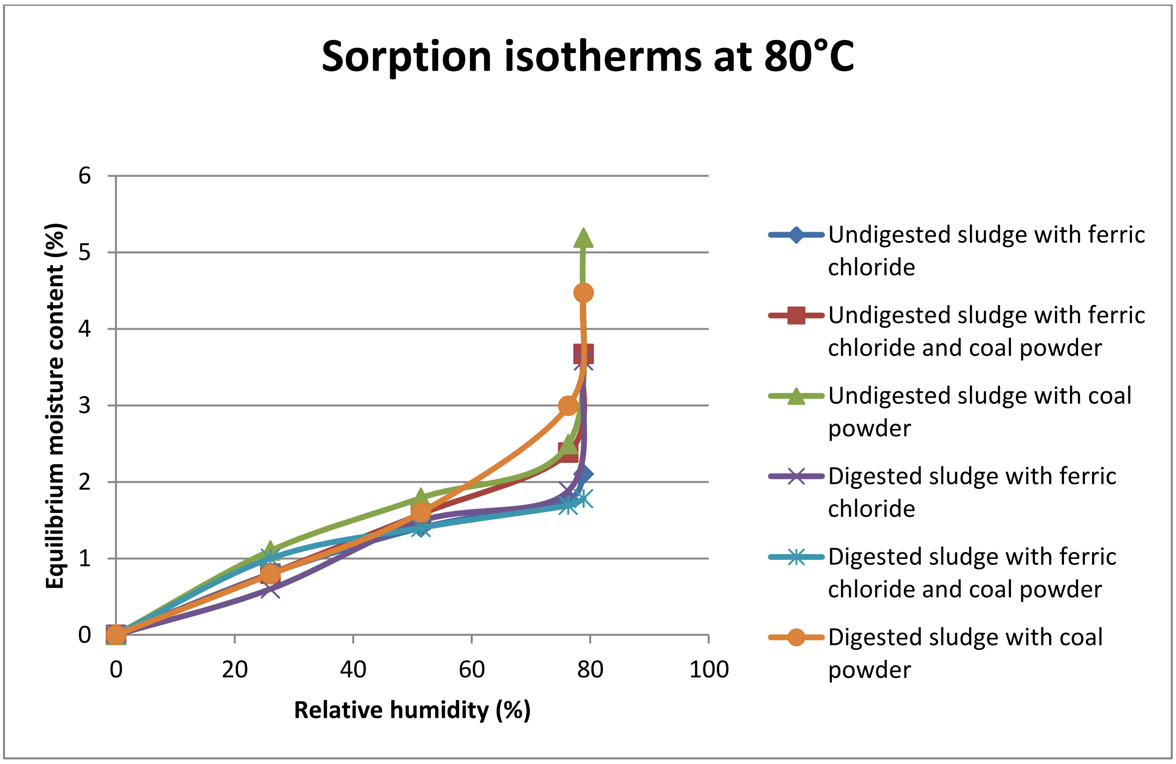


Fig 7: Sorption isotherms at 80°C

Chapter 5: Conclusions and recommendations

5.1 Introduction

This chapter describes the conclusions based on the results of the dewatering and sorption experiments. Recommendations to carry out further experiments on the effect of coal powder and ferric chloride on the dewatering and drying process of sludge are also made.

5.2 Conclusions

1.) It is shown that adding coal powder to any type of sludge increases the chemical dewatering and dry solid contents.
2.) Undigested sludge gives better dewatering results and higher dry solid contents in all experimental setups, then digested sludge.
3.) Undigested sludge with coal powder gives the best dewatering results and highest dry solid content with an average of 44%.
4.) When using coal powder in undigested sludge, ferric chloride isn’t needed anymore.
5.) When using digested sludge the best dewatering results were achieved using a combination of ferric chloride and coal powder.
6.) Sludge of any type in this experimental setup didn’t adsorb much water and all types of sludge adsorbed roughly the same amount of water.
7.) Additives like coal powder and ferric chloride in the sludge didn’t affect the way the sludge adsorbed water from the air and therefore don’t affect the way sludge dries.
8.) There is hardly any difference between undigested and digested sludge in the drying process.

Overall conclusion

The combined results of this research show four important things:

- Coal powder has a positive effect on chemical dewatering
- Ferric chloride isn’t needed anymore in chemical dewatering when using coal powder
- Undigested sludge gives much better dewatering results
- Additives or the type of sludge don’t affect the drying of sludge

This will lead to less water per mass of sludge and less natural gas is needed to evaporate the water. By cancelling out the use of ferric chloride, we also reduce the costs of the sludge treatment process. Because ferric chloride and coal powder don’t affect the drying step in the sludge treatment process, A WWTP can use these results to optimize their sludge treatment process. You would create a more durable process and at the same time reduce the costs involved in sludge treatment.

5.3 Recommendations

The challenge in the future is to develop a way to incorporate the use of coal powder in the sludge treatment process. At the WWTP of Garmerwolde they digested the sludge first and use the biogas as energy. Undigested sludge however gave much better dewatering results. Further investigations must be done which method is economically better for the WWTP.

It would also be interesting to see what the desorption isotherms are of sludge directly after the press. Desorption isotherms let us see how much water sludge can transport to the air. With both desorption and adsorption we could better estimate the effect of the additives on the drying of sludge.

Not much time was spent to optimize the dewatering results within the experiments, because it wasn't the goal of this research. To achieve higher dry solid contents especially with digested sludge, optimizing the stirring intensity and time are necessary. They are the two most important parameters that couldn't be controlled in the right way. Different types of sludge acquired at other WWTP's might also give other results.

Literature

1. *Performance evaluation of an inclined filter using coagulation/flocculation aids for the removal of suspended solids and phosphorus from micro screen backwash effluent*, **J.M. Ebeling, C.F. Welsh, K.L. Rishel,** Aquacultural Engineering 35 (2006) 61-77

2. Thesis: *Sludge handling cost reduction at the WWTP of Garmerwolde*, **Olivier Burgering**, page: 8-10, 22-23, 14 November 2011

3. Waterschap Noorderzijlvest, Folder RWZI Garmerwolde: *De rioolwaterzuiveringsinstallatie in Garmerwolde in acht stappen*, September 2007

4. http://www.uacg.bg/filebank/att_1846.pdf, *Coagulation and Flocculatioin: Process Fundamentals*, page: 199-205.

5. *Solids/Liquids Separation*, **Paul N. Cheremisinoff**, page: 341-344, 353-354

6. *Coagulation and Flocculation in water and wastewater treatment*, **John Bratby**, page: 1-5

7. Thesis: *Coal improved mechanical dewatering of sludge*, **Gijsbert Haaksman**, page: 11, 19-20, 28 May 2009

8. Thesis: *Mechanical dewatering of sewage sludge using particle aided filtration at Water Board Noorderzijlvest*, **Martin Meelker**, Appendix G

9. *Effect of coagulation conditions on the dewatering properties of sludges produced in drinking water treatment*, **David I. Verrelli, David R. Dixon, Peter J. Scales**, 11 March 2009

10. *The Seperation Method for removing of colloidal particles from raw water*, **A. Koohestanian, M. Hosseini and Z. Abbasian**, American-Eurasian J. Agric. & Environ. Sci., 4 (2): 266-273, 2008 ISSN 1818-6769

11. http://www.snf-group.com/IMG/pdf/Water_Treatment_3_E.pdf, Sludge Dewatering, page: 4-6.

12. *Humidity Fixed points of binary saturated aqueous solutions*, **Lewis Greenspan**, JOURNAL OF RESEARCH of the National Bureau of Standards-A. Physics and Chemistry, Vol. 81 A, No. 1, January-February 1977

13. *Moisture sorption isotherm and isosteric heat of sorption characteristics of starch based edible films containing antimicrobial preservative*, **Chowdhury, T. And Das, M.** International Food Research Journal 17: 601-614 (2010)

14. *The rate of drying solid materials*, **W. K. Lewis**, The journal of industrial and engineering chemistry, May 1921

15. http://www.nzifst.org.nz/unitoperations/drying4.htm, Unit operations in food processing, chapter 7

Appendix A: Description of the used equipment, sludge and chemicals

The filter press:

In the dewatering experiments, a lab-scale filter press was used. The filter press exists of a mechanical press connected to a computer to collect data. The computer also controls the press, pressing time, maximum pressure and pressure curve can be adjusted.

Mixing equipment:

The mixing equipment used was a rectangle mixer blade with eight holes in it. The mixer blade was attached in a rotating device with controllable rpm and mixing time. The mixing beaker (around 250 mL) is a metal cylinder with four baffles on the inside. After some optimization experiments shown in table 1, we came to the conclusion we could best use a stirring intensity of 600 rpm. This gave the best floc formation and dewatering result.

Table 1: effect of stirring intensity on DSC of sludge

Experiment	**Stirring intensity (rpm)**	**DSC (%)**
1	500	17.27
2	600	22.38
3	700	15.09
4	800	12.94
5	900	15.26
6	1000	18.01
7	1100	14.59
8	1200	12.48
9	1300	4.73
10	1400	5.95

Stirring intensities below 600 rpm resulted in unfinished floc forming and a lower dry matter content. Stirring intensities higher than 600 rpm resulted in loss of sludge during mixing. It was highly impractical because all the sludge splatted everywhere. This problem was caused by the height of the mixing beaker. If a higher mixing beaker was used, the spatting couldn't be a problem. At even higher stirring intensities above 1200 rpm we experienced floc breaking that resulted in very bad dry matter contents. A stirring time of 3 seconds was used and resulted in the best dewatering results. Stirring times higher than 3 seconds resulted in floc breaking and lower stirring times in unfinished floc forming.

Drying equipment:

The oven used for drying is standard lab oven. The sludge cake samples were dried at 105°C for about 18 hours. This was enough time to evaporate all the water.

Sludge:

Two different kinds of sludge were used in the experiments. Undigested sludge which consists of primary and secondary sludge, and digested sludge which is called mixed sludge. The sludge was collected in batches of 10 liter from the WWTP of Garmerwolde and stored at 5°C in a cooling room. The input d.s. of the sludge is measured in three fold and used to calculate the amount of extra water needed to get a DSC of 3%. In the first experiments, used to find the optimum amounts of additives, 100 mL of sludge was used. We found out that, to achieve better and more accurate results, it was better to weigh the sludge. After that we used in each experiment 81 grams of sludge.

Used chemicals:[8]

Polyelectrolyte (PE):

In the experiments we used the PE Praestol K. The PE obtained from the WWTP of Garmerwolde is stored in plastic flasks at 5°C. Before PE could be used, it was first heated in the oven to room temperature. The original PE in the bottle (1% active PE and 99% water) was diluted to a solution of 1:10 (0.1% active PE). This was done, because the original PE was too viscous to use. The optimum amount of for 100 mL sludge is 25 mL of PE. For 81 grams of sludge the optimum amount was 20 mL.

Ferric chloride ($FeCl_3$):

The ferric chloride was obtained from the WWTP of Garmerwolde. If used, the original $FeCl_3$ (40% active) is diluted to a solution of 1:10 (4% active). A fixed amount of ferric chloride was used after we determined the optimum amount. The optimum amount for 100 mL of sludge is 3.5 mL of ferric chloride solution. For 81 grams of sludge the optimum amount was 2.8 mL.

Coal powder:

The coal powder used in the experiments had a DSC of 95%. All of the conducted experiments were carried out using a particle size of d<100 µm. The coal powder is very inexpensive and therefore an attractive choice as additive.

Appendix B: Unprocessed data of dewatering experiments

Measurements digested sludge:

Exp.	Sludge (g)	Coal (g)	$FeCl_3$ (mL)	PE (mL)	Beaker (g)	Beaker with sample (g)	Beaker with sample after drying (g)	DSC (%)
1	81	0.81	2.8	20	3.035	12.92	5.68	26.75
2	81	0.81	2.8	20	3.022	13.66	5.80	26.10
3	81	0.81	2.8	20	3.032	12.96	5.79	27.76
4	81	0.81	2.8	20	3.026	12.99	5.77	27.53
5	81	0.81	2.8	20	3.024	14.96	5.67	22.16
6	81	0	2.8	20	3.034	18.80	5.074	12.94
7	81	0	2.8	20	3.050	26.96	5.16	8.83
8	81	0	2.8	20	3.028	18.79	5.31	14.48
9	81	0	2.8	20	3.021	19.65	5.13	12.66
10	81	0	2.8	20	3.027	19.39	4.81	10.87
11	81	0.81	0	20	3.027	18.80	5.76	17.36
12	81	0.81	0	20	3.029	17.29	5.61	18.09
13	81	0.81	0	20	3.030	20.61	5.80	15.77
14	81	0.81	0	20	3.031	20.32	5.67	15.29
15	81	0.81	0	20	3.022	19.49	5.63	15.83

Measurements undigested sludge:

Exp.	Sludge (g)	Coal (g)	$FeCl_3$ (mL)	PE (mL)	Beaker (g)	Beaker with sample (g)	Beaker with sample after drying (g)	DSC (%)
1	81	0	2.8	20	3.023	9.16	4.90	30.56
2	81	0	2.8	20	3.031	13.54	4.96	18.31
3	81	0	2.8	20	3.018	11.71	4.97	22.43
4	81	0	2.8	20	3.023	8.49	4.72	31.00
5	81	0	2.8	20	3.016	13.70	4.97	18.30
6	81	0.8	2.8	20	3.033	14.03	6.00	27.02
7	81	0.8	2.8	20	3.050	10.47	5.70	35.75
8	81	0.8	2.8	20	3.029	11.28	5.71	32.46
9	81	0.8	2.8	20	3.020	13.01	5.71	26.89
10	81	0.8	2.8	20	3.026	17.37	5.64	18.19
11	81	0.8	0	20	3.016	9.18	5.78	44.91
12	81	0.8	0	20	3.010	9.57	5.95	44.86
13	81	0.8	0	20	3.049	9.74	5.96	43.52
14	81	0.8	0	20	3.028	10.64	6.09	40.30
15	81	0.8	0	20	3.031	9.70	5.98	44.26

Appendix C: Unprocessed data of sorption experiments

20°C sorption isotherm of undigested sludge with $FeCl_3$

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	29.390	1.001	30.391	30.405	0.014	1.40
NaBr	34.547	1.032	35.579	35.598	0.019	1.84
NaCl	33.131	1.016	34.147	34.182	0.035	3.45
KCl	37.151	1.020	38.171	38.221	0.050	4.90

20°C sorption isotherm of undigested sludge with $FeCl_3$ and coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	34.119	1.030	35.149	35.173	0.024	2.33
NaBr	32.977	1.018	33.995	34.028	0.033	3.24
NaCl	26.685	1.017	27.702	27.754	0.052	5.11
KCl	34.623	1.029	35.652	35.719	0.067	6.51

20°C sorption isotherm of undigested sludge with coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	28.365	1.008	29.373	29.386	0.013	1.29
NaBr	32.158	1.011	33.169	33.197	0.028	2.77
NaCl	34.247	1.006	35.253	35.287	0.034	3.38
KCl	31.002	1.020	32.022	32.073	0.051	5.00

20°C sorption isotherm of digested sludge with $FeCl_3$

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	18.569	1.012	19.581	19.589	0.008	0.79
NaBr	17.632	1.008	18.640	18.659	0.019	1.88
NaCl	14.875	1.009	15.884	15.908	0.024	2.38
KCl	16.369	1.005	17.374	17.408	0.034	3.38

20°C sorption isotherm of digested sludge with $FeCl_3$ and coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	20.364	1.009	21.373	21.385	0.012	1.19
NaBr	19.596	1.003	20.599	20.618	0.019	1.89
NaCl	18.372	1.004	19.376	19.405	0.029	2.89
KCl	19.412	1.011	20.423	20.455	0.032	3.17

20°C sorption isotherm of digested sludge with coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	16.687	1.007	17.694	17.700	0.006	0.60
NaBr	14.351	1.006	15.357	15.372	0.015	1.49
NaCl	13.287	1.013	14.300	14.332	0.032	3.16
KCl	17.214	1.015	18.229	18.277	0.048	4.73

50°C sorption isotherm of undigested sludge with $FeCl_3$

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	15.862	1.014	16.876	16.884	0.008	0.79
NaBr	20.159	1.015	21.174	21.191	0.017	1.67
NaCl	19.680	1.009	20.689	20.714	0.025	2.48
KCl	14.759	1.006	15.765	15.804	0.039	3.88

50°C sorption isotherm of undigested sludge with $FeCl_3$ and coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	18.108	1.034	19.142	19.147	0.005	0.48
NaBr	18.373	1.008	19.381	19.392	0.011	1.09
NaCl	16.384	1.041	17.425	17.440	0.015	1.44
KCl	20.213	1.033	21.246	21.264	0.018	1.74

50°C sorption isotherm of undigested sludge coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	20.561	1.011	21.572	21.579	0.007	0.69
NaBr	16.916	1.020	17.936	17.945	0.009	0.88
NaCl	13.843	1.011	14.854	14.868	0.014	1.38
KCl	17.291	1.007	18.298	18.326	0.028	2.78

50°C sorption isotherm of digested sludge with $FeCl_3$

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	19.125	1.005	20.130	20.136	0.006	0.60
NaBr	18.657	1.018	19.675	19.689	0.014	1.38
NaCl	15.874	1.021	16.895	16.927	0.032	3.13
KCl	16.225	1.008	17.233	17.284	0.051	5.06

50°C sorption isotherm of digested sludge with $FeCl_3$ and coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	14.854	1.006	15.860	15.867	0.007	0.70
NaBr	15.368	1.004	16.372	16.385	0.013	1.29
NaCl	19.254	1.015	20.269	20.295	0.026	2.56
KCl	17.547	1.012	18.559	18.598	0.039	3.85

50°C sorption isotherm of digested sludge and coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	19.019	1.005	20.024	20.036	0.012	1.19
NaBr	15.302	1.008	16.310	16.334	0.024	2.38
NaCl	14.098	1.014	15.112	15.148	0.036	3.55
KCl	16.541	1.013	17.554	17.606	0.052	5.13

80°C sorption isotherm of undigested sludge with $FeCl_3$

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	17.293	1.004	18.297	18.305	0.008	0.80
NaBr	16.918	1.003	17.921	17.935	0.014	1.40
NaCl	17.627	1.016	18.643	18.661	0.018	0.89
KCl	16.384	1.001	17.385	17.406	0.021	2.10

80°C sorption isotherm of undigested sludge with $FeCl_3$ and coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	17.629	1.005	18.634	18.642	0.008	0.80
NaBr	16.382	1.010	17.392	17.408	0.016	1.58
NaCl	18.108	1.008	19.116	19.138	0.024	2.38
KCl	18.372	1.008	19.380	19.417	0.037	3.67

80°C sorption isotherm of undigested sludge with coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	18.109	1.002	19.111	19.122	0.011	1.10
NaBr	17.292	1.003	18.295	18.313	0.018	1.79
NaCl	20.561	1.006	21.567	21.592	0.025	2.49
KCl	13.843	1.001	14.844	14.896	0.052	5.19

80°C sorption isotherm of digested sludge with $FeCl_3$

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	20.214	1.002	21.216	21.222	0.006	0.60
NaBr	20.560	1.005	21.565	21.580	0.015	1.49
NaCl	20.215	1.011	21.226	21.245	0.019	1.88
KCl	18.371	1.006	19.377	19.413	0.036	3.58

80°C sorption isotherm of digested sludge with $FeCl_3$ and coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	16.383	1.005	17.388	17.398	0.010	1.00
NaBr	17.628	1.001	18.629	18.643	0.014	1.40
NaCl	17.291	1.004	18.295	18.312	0.017	1.69
KCl	28.841	1.012	29.853	29.871	0.018	1.78

80°C sorption isotherm of digested sludge and coal powder

Salt solution	Petri dish(g)	Sample (g)	Petri dish + sample (g)	Petri dish + sample + adsorbed water (g)	Amount of adsorbed water (g)	Percentage adsorbed water by sample (%)
MgCl	18.109	1.007	19.116	19.124	0.008	0.79
NaBr	13.843	1.003	14.846	14.862	0.016	1.60
NaCl	16.916	1.004	17.920	17.950	0.030	2.99
KCl	20.212	1.006	20.218	21.263	0.045	4.47