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LINDA SUVANTO
MODELING FILTERABILITY OF BIOMASS BASED SLURRIES

Master of Science thesis

Examiner: TUT Industry Professor
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ABSTRACT

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The aim of this thesis was to investigate factors, which has the most effect on slurry filterability, and to create a model predicting filterability from collective slurry charasteristics with different slurries and process conditions. The work is focused on cake filtration, which is a major solid-liquid separation method in wide range of industries. The work consists literature review, experimental part and modeling part.

In the experimental part both filterability and the material properties of different slurries were investigated. Filtration tests series consisted comparing filterability with eight different biomass based slurried in the same process conditions, but also a wider test series which investigated the effect of temperature and pressure was committed with three slurries. Also individual tests considering changes in pH, effect of selected filter cloth and effect of slow pressure increase was investigated. The slurry properties were either measured in laboratory or collected from literature. The measured slurry properties were selected based on literature review, being particle size, shape and density, liquid density and viscosity, zeta-potential and conductivity.

The results of the work are, that especially slurry pH and particle interactions have a remarkable role on filterability. Instead, particle size distribution did not have a clear effect on filterability with slurries used in this work, even though particle size is widely recognized to be a decisive parameter affecting filterability in literature. The created model give remarkably better estimation of filterability compared to the convinental models, but because of the complication of filtration, a perfect model could not be created. More investigation is needed esipecially considering how different interparticle forces effect on filterability.

TIIVISTELMÄ

LINDA SUVANTO: Biomassapohjaisten lietteiden suodattuvuuden mallinnus
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Tämän työn tarkoituksena oli selvittää ne tekijät, joilla on suurin vaikutus lietteen suodattuvuuteen, sekä rakentaa malli jonka avulla lietteen suodattuvuutta on mahdollista ennustaa lietteen ominaisuuksien perusteella. Työ koskee kakkusuodatusta, joka on yleinen kiinteä-neste -erotusmenetelmä lukuisilla eri teollisuudenaloilla. Työ sisältää kirjallisuusselvityksen, kokeellisen osuuden sekä mallin määrityksen.

Kokeellisessa osuudessa tutkittiin erilaisten lietteen suodattuvuutta ja niitä materiaaliominaisuuksia, jotka suodattuvuuteen eniten vaikuttavat. Suodatuskokeissa vertailtiin kahdeksan lietteen suodattuvuutta samoissa olosuhteissa, mutta myös laajempi koesarja jossa tutkittiin lämpötilan ja paineen vaikutusta suodatusnopeuteen tehtiin kolmella lietteellä. Lisäksi yksittäisissä koesarjoissa tutkittiin myös pH:n muutoksen, kankaan valinnan ja hitaan paineen noston vaikutusta. Tiedot lietteiden ominaisuuksista saatiin osin laboratoriomittauksilla ja osin kirjallisuuslähteiden perusteella. Tarkasteltavat ominaisuudet valittiin kirjallisuusselvityksen pohjalta, ja ne olivat partikkelien kokojakauma, muoto ja tiheys, nesteen tiheys ja viskositeetti sekä suodoksesta mitatut zeta-potentiaali ja sähkönjohtavuus.

Tutkimuksen perusteella selvisi, että erityisesti lietteen pH:lla ja partikkelien välisillä vuorovaikutuksilla on merkittävä vaikutus suodattuvuuteen. Sen sijaan partikkelien kokojakaumalla ei ollut selvää vaikutusta suodattuvuuteen tässä työssä käytetyillä lietteillä, vaikka kokojakaumalla on kirjallisuudessa laajalti todettu olevan erittäin suuri vaikutus suodatusnopeuteen. Kehitetty malli antaa merkittävästi paremman arvion suodattuvuudesta kuin perinteiset mallit, mutta suodattuvuuden monimutkaisuuden vuoksi täydellistä mallia ei kyetty rakentamaan. Lisää tutkimusta tarvitaan etenkin partikkelien välisten voimien vaikutuksesta suodattuvuuteen.

PREFACE

This Master's Thesis was made for Valmet Technologies from March 2017 to December 2017. I am grateful for getting the opportunity of doing this thesis, with an interesting and versatile topic. I feel that I have learned a lot through this project. Firstly, I want to thank my supervisor at Valmet, Tuomo Hilli, and professor Tero Joronen for help, comments and ideas during this work. Both gave me numbers of good advices and support, which I am grateful.

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Tampere, 23.1.2018

Linda Suvanto

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

DLS	Dynamic Light Scattering
DLVO	Derjaguin, Landau, Verwey and Overbeek
PSD	Particle size distribution
SCR	Specific cake resistance
SSA	Specific surface area

A	filter area [m^2]
B	value of intercept [-]
c	mass of solids per unit volume of filtrate [kg/mm^3]
d_{vg}	geometric mean diameter of particle size [μm]
k	permeability [-]
K_s	value of the slope [-]
K	Kozeny constant [-]
K_{FC}	filterability parameter [s^{-1}]
$l(t)$	cake thickness [m]
m	moisture ratio [-]
N	number of capillaries [-]
n	compressibility index [-]
n	non-Newtonian index [-]
Q	filtrate flow rate [m/s]
$R(t)$	equivalent radii of capillary tubes [m]
R_c	cake resistance [1/m]
R_m	medium resistance [1/m^2]
S_0	specific surface area [m^{-1}]
s	slurry concentration [w/w]
V	volume of filtrate [m^3]
w	cake mass per unit area [kg/m^2]
W	cake mass [kg]
x_{sv}	Sauter diameter [μm]

α	cake specific resistance [m/kg]
α_0	cake specific resistance at P_0 [m/kg]
α_{av}	average cake specific resistance [m^{-2}]

β	empirical coefficient [-]
ΔP	pressure difference [Pa]
ϵ	cake porosity [-]
ϵ_0	cake porosity at P_0 [-]
κ	dynamic shape factor [-]
μ	viscosity [Pa s]
ρ_p	particle density [kg/m^3]
ρ_l	liquid density [kg/m^3]
σ_g	geometric standard deviation [-]
ϕ_p	sphericity [-]
ϕ	solidosity [-]

1. INTRODUCTION

Filtration is a commonly used solid-liquid separation method, where solid-liquid mixture is towarded to a porous medium. The solid phase get stuck on the medium, creating a filter cake, while the liquid phase flows through the medium. Filtration has been used from early biblical times mainly for water purification, but is nowadays used in many applications in wide range of industries, such as pharmaceutical, chemical and forest industry, to name just a few. The purpose in filtration is usually either the purification of the liquid phase or the recovery of the solid phase, or even the recovery of both or even neither phase. When the desire in filtration is the recovery of the solid phase, which is typical in biorefining technologies, the purpose is to achieve high filterability and high dry matter content in filter cakes.

Filtration has many advantages, and it's energy-efficiency and cost-efficiency often makes it the preferred choice compared to other separation methods. One advantage with filtration is it's versatility with different particle sizes - filtration can be used from coarse to colloidal particles. How filtration succeeds, affects greatly to success of the whole process, since filtration does have a great effect on the product yield, economics and quality aspects. Despite of it's importance, filtration have not gathered that much attention in academic research that it deserves. Hence, filtration can be said to be the inconspicuous process with great importance.

Even though the filtration process is widely used and has a long history, an accurate model for predicting filterability from collective slurry characteristics have not been invented till date, and equipment design is still mostly made based on filtration experiments. Equations for calculating pressure loss through the filter cake, fluid flow through porous bed and particle deposition in the cake have been invented, which are nowadays used also describing filterability. Different models have been created over the years, but most of them are suitable for a limited situations, and only few are based on slurry characteristics. The difficultly to model filtration is understandable, since in filtration both solids and liquid move, filter channels deform and particles and liquid have also chemical interactions between each other. Also the new applications with difficultly-filterable slurries mostly in field of biotechnology have created new challenges. The need to study the filtration process and phenomenon continues.

With this study, the aim is to recognize the slurry properties, which have the greatest effect on filterability. The target is to investigate, is it possible to predict slurry filterability by measuring these properties. Based on the knowledge of the most important properties affecting filtration, the aim is to create a model to predict filterability. The work considers cake filtration of biomass based slurries. Also the effect of process variables, mainly temperature and pressure, to the filterability is investigated. Measuring local filtration data is important part in filtration modeling, and also in this study, a test series with specific slurries are committed. Based on those tests, the results are compared with existing cake filtration models, and they are modified to achieve an accurate but still user-friendly model for predicting filterability.

This thesis includes total eight chapters. In the second chapter, filtration fundamentals, a short review of filtration methods, equipment and pretreatment techniques is taken. In Chapter 3 is theoretical background of filtration, where slurry properties affecting on filterability are discussed and their importance to overall filtration efficiency is investigated. Discussed variables are particle properties such as particle size and shape, nature of the fluid which refers to density and viscosity, interactions with particles and liquid and the resistance of the filter media. Also the properties of the formed filter cake - it's compressibility, resistance, porosity and permeability - are discussed. In Chapter 4 is an overview of the most wide-known calculations of cake formation and fluid flow through the cake. The represented equations come as far as from the 18th century, when Darcy's law was created. After that also Ruth's conventional filtration theory and Kozeny-Carman equation have become major calculation basis in filtration modeling. Experimental part and mathematical modeling are represented in Chapters 5 and 6, and conclusions can be read from Chapter 7.

2. FILTRATION FUNDAMENTALS

Cake filtration is one of most frequently used filtration process. In the beginning of cake filtration, a porous layer separates the particles, while the liquid flows trough the medium. These particles which get stuck on the filter medium create the filter cake. This formed cake starts to work as part of the process, blocking particles not just on the cake surface, but also inside of the filter cake. [1] In this chapter, the filtration fundamentals are introduced. A short review of solid-liquid separation stages, filtration methods, equipment and pretreatment techniques is taken.

2.1 Stages of solid-liquid separation

Cake filtration, though a common way to separate particles from a liquid, is still only a small part in the field of solid-liquid separation. Many separation processes have been developed over the years. In Figure 2.1 is one way to show the relationship between these processes. In separation system design, all of these stages should be considered. Separation stages are pretreatment, solids concentration, solid separation and post-treatment. Separation process includes always at least one of these methods, but usually several of these processes are used. The stages and different alternatives are described in greater detail below. [2]

Pre-treatment is used mostly with difficultly filterable slurries. It usually includes changing the slurry properties chemically or physically, and therefore create it to more easily filterable form. Pre-treatment processes are discussed further in Ch. 2.4. In solids concentration, the liquid is separated without the filtration process by, for example, gravitational or centrifugal forces. The aim is to increase the solids concentration, so the actual filtering is faster. New techniques have also been developed in addition to improve the solids concentration process, such as separation by magnetic, electrical or sonic force fields. Use of these new methods is still uncommon in practice. In solid-liquid separation, the actual filtering occurs. Two different filtration methods are divided as cake filters and depth filters. Both

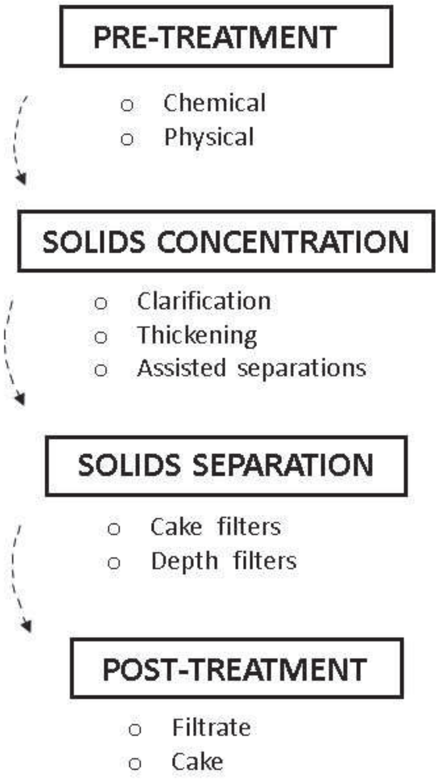


***Figure* 2.1** *Components of the separation process [2]*

filtering types includes many different filters. Different cake filters include pressure, vacuum, centrifugal and gravity filters, and different depth filters include granular beds, cartridges, precoat-filters and crossflow filters. In the post-treatment part, improvements are made to the solid product, the filter cake, or to the liquid product called as filtrate. The aim of these improvements are to increase the quality of these products for example by polishing or decolourisation the filtrate or by consolidating, washing, deliquoring or drying the cake. [2]

In actual operation, the filtration is usually made with the same equipment than some of the post-treatment processes, such as cake washing and air drying. These different phases made one after the other create cake filtration cycle. The cycle describes the time at which all the phases are committed, and the process can be started from the beginning again. A full cake filtration cycle consists commonly filtration, pressing, cake washing and air drying, but it depends on the process which of these are used. Figure 2.2 shows filtration, cake pressing and deliquoring. [3, 4]

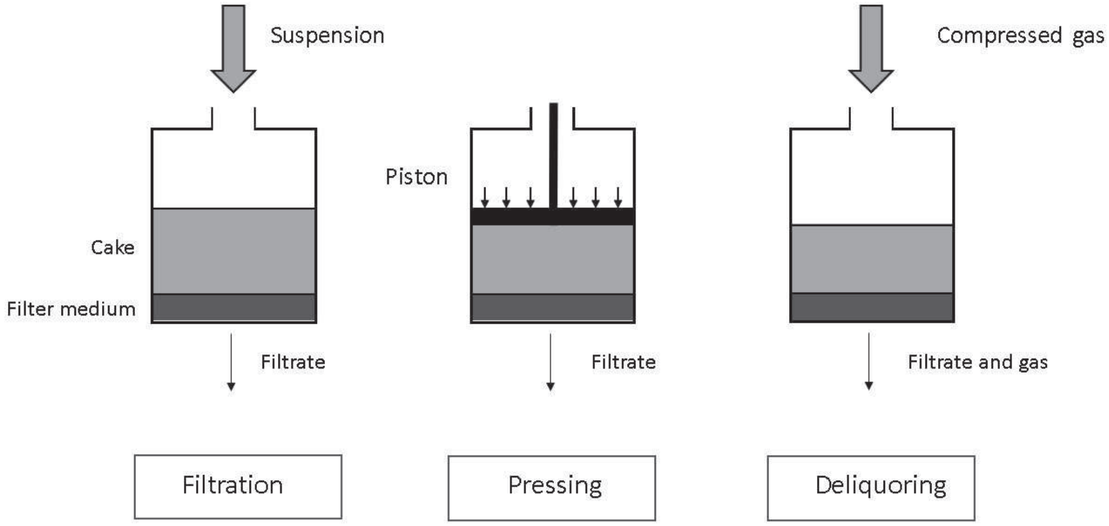


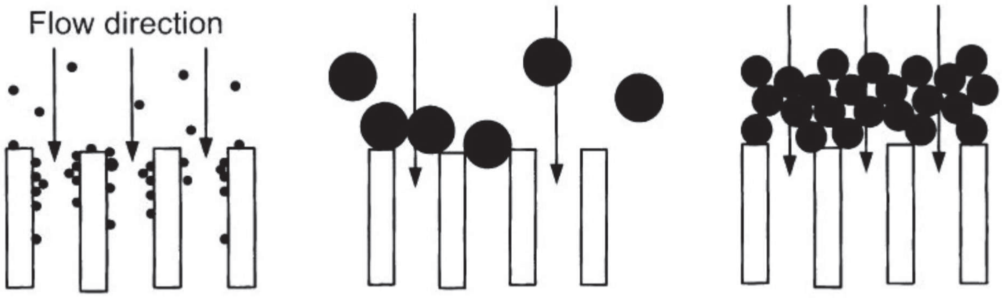
Figure *2.2 Filtration cycle [4]*

Cake washing is a process, where soluble impurities are removed from the filter cake. The reason is usually either remove impurities from a more valuable solid product, or to increase the recovery of a liquid product. In cake washing, wash liquor is added on the top of the filter cake, and forced to flow through the cake using pressure difference. Cake pressing describes separating solids and liquids by compression. In cake pressing stage, the formed filter cake is compressed with a sheet by a direct contact, which causes compression especially in organic material. It is usually done after filtration and before washing and deliquoring. Deliquoring is a term for desaturation of a filter cake. It is made either by sucking or blowing gas through the filter cake, causing part of the liquid exit from the cake. Deliquoring is also called as dewatering or air blowing. [2]

2.2 Filtration laws

Laws of filtration were originally created by Hermans and Brédee [5] in 1935, but have been studied more by many other investigators. The laws describe three different methods, how a particle acts while arriving at the filter medium surface. Figure 2.3 shows these three different filtration methods, which are called as standard blocking filtration, complete blocking filtration and bridging filtration.

Figure 2.3(a) shows standard blocking filtration, where particle size is smaller than the pore size. Standard blocking filtration law assumes that particles are deposited on the pore walls. This causes the pore volume to decrease as filtrate is produced. A filter cake is not created on the filter medium, since all the particles are being trapped in the pore walls. The trapping occurs due diffusional, inertial or electrostatic effects, and the method insists low particle concentration in the feed. Figure 2.3(b) shows complete blocking law, where particles are bigger than pore sizes and are completely blocked by the filter medium. Particle concentration is low or medium, and the capture occurs by sieving or screening. When particle reaches the medium, and seals the pore, blocking occurs. If all pores get blocked, the filtrate cannot flow through the pores and the flow stops immediately. Figure 2.3(c) shows bridging filtration law, also called as cake filtration law, which is caused when particles form a bridging on the media. These bridges are quite stable, and a cake layer can be formed on the bridge. Bridging can occur when particle size is smaller than the pore size. This method demands high concentration of particles in feed. [2]



(a) Standard blocking (b) Complete blocking (c) Bridging

***Figure* 2.3** *The laws of filtration [2]*

The laws of filtration give basic understanding of the different filtration methods, which happen when particles interact with the filter media surface. Nevertheless, they do not give further understanding of the particle deposition. That's why the filtration laws are mainly used for visualizing the phenomenon, and actual use in filtration calculations is limited. [2]

2.3 Filtration equipment

Filtration equipment can be classified based on the affecting force. Tarleton and Wakeman [4] presented a board categorization of filtration equipment selection based on the affecting force. The most common forces are gravity, vacuum, pressure and centrifugal forces, but also other force fields such as magnetic, electrical or ultrasonic fields exist. These types can be classificated more based on the flow rate - if the equipment is working continuously, semi-continuously or in a batch. With pressure filters, the flow type can also be variable volume. Different filter types are presented below by Rushton [1], divided by the affecting force.

- Gravity: Strainer or Nutsche, Sand-Charcoal Filter, Sieve Bends, Rotary Screen, Vibratory Screen
- Vacuum: Nutsche Filter, Andle and Cartridge, Table or Pam Filter, Rotary Drum, Horizontal Belt
- Pressure: Pressure Nutsche, Plate and Frame Filter, Tube, Candle and Leaf Filter, Belt press, Screw Press
- Centrifugal: Basket/Basket Centrifuge, Vibratory and Tumbler Centrifuge, Helenical Conveyor

The equipment selection is quite wide. It is possible, since filtration is included in a great amount of industrial processes in many different fields. A simple classification for determining the most suitable solid-liquid separation equipment for a certain process don't exist, since the wide range of different slurry and filter properties make the equipment selection complicated. For accurate evaluation laboratory tests are necessary. Nevertheless, Lloyd and Ward have created a simplified map, see Fig. 2.4, for helping the selection of the most appropriate equipment. The selection criteria consist particle size and slurry concentration, which are the most important parameters in equipment selection. [6] The minimum solids concentration required to use cake filtration depends on the solid and medium properties, but is typically around 0.5% by volume. [7]

Beside the particle size and the slurry concentration, one important aspect in equipment selection is the aim of the filtration. If the purpose is the recovery of the solid phase, using deep bed filters or precoat filters is not reasonable. Also a great number of other variables affect on the equipment selection making it more complicated. Therefore the Figure 2.4 can only be seen as basis of equipment selection in solid-liquid separation. [6]

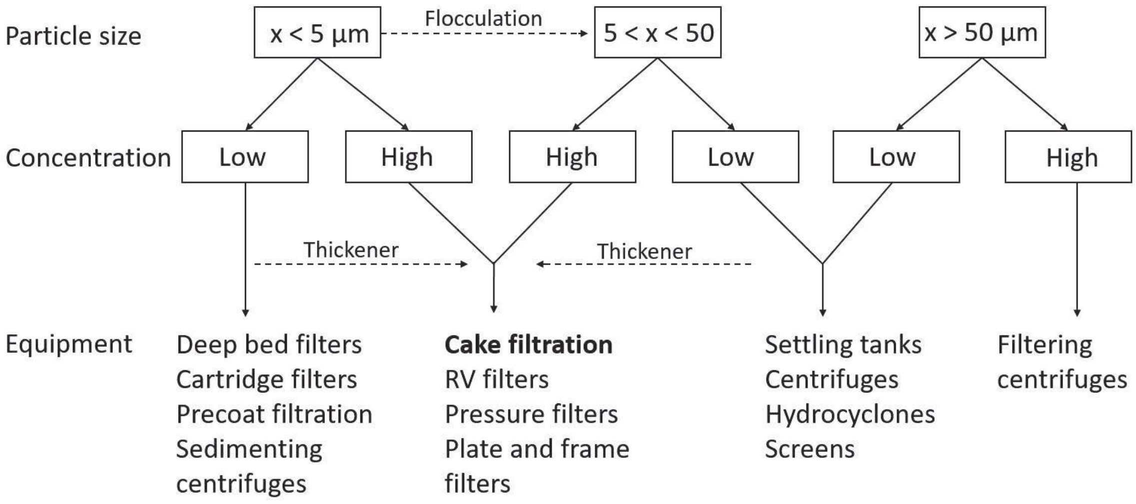
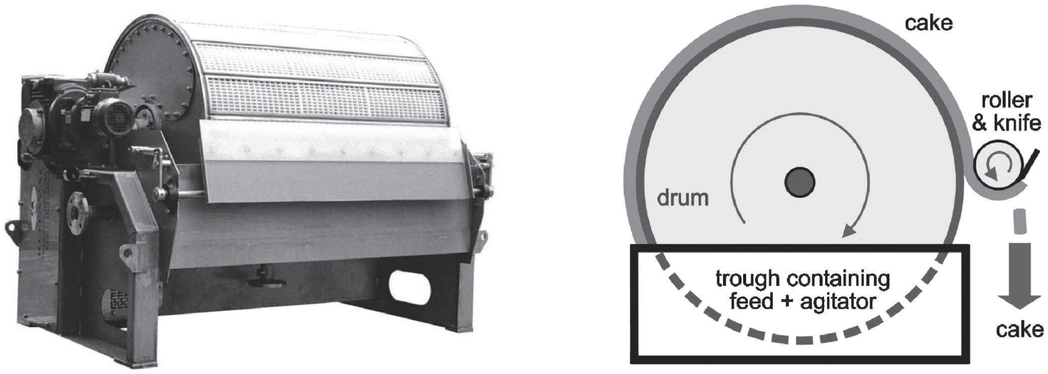


Figure 2.4 *Equipment selection [6, p. 31]*

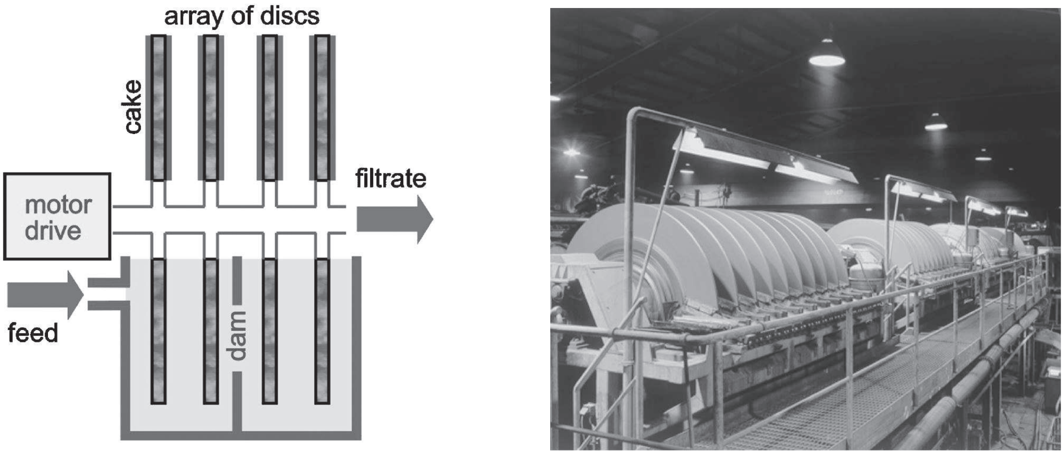
Figure 2.5 shows Rotary vacuum drum filter, with external filtering surface. In Fig. 2.5(a) is presented the cake discharge using knife or scraper, and in Fig. 2.5(b) cake discharge with roller and knife. Also other methods for cake discharge exist, such as discarding cake using belt discharge, where endless cloth passes around its outer periphery and at certain point the movement causes the cake to be released. The slurry can be added to the filter from the bottom, as in the figures, or from the top of the drum. The presented drum filters are operated by vacuum, but using pressure as the driving force is also possible, though more seldom used. The advantage with drum filters is the capability to continuous operation, and disadvantage the need of rather steady slurry properties. Typical use for drum filters are for separating relatively easy to filter suspensions. Particle size range is usually 1-200 μm, and concentration 1-20 % w/w. Most commercial unit have the filtration area in range 1-80 m^2. [4, 8]

Figure 2.6 shows disc filters. In Fig. 2.6(a) is the cut-off scheme of the filter, and in Fig. 2.6(b) a real-life picture of actual filter in operation. Disc filters have similar operation principle as rotary drum filters. The major difference is the design; the filter area consists several discs, which are placed radially around the shaft. Because of the structure, disk filters can be fitted to a remarkable smaller area compared to drum filter, but the tight structure also causes the cake washing to be less efficient. Therefore, disc filters are fitted most suitable for situations, where cake washing is not needed and the filtration have to be committed in a relatively small area. [8]



(a) cake discharge with knife/scraper (b) cake discharge with roller and knife

Figure 2.5 *Rotary vacuum drum filter [4]*



(a) Cut-off scheme (b) Actual filter

Figure 2.6 *Disc filter [4]*

Figure 2.7 shows Vertical pressure filter, which consists varying number of flat plates, which are pressed together to form series of chambers, where the slurry can be poured. The plate is covered with filter cloth. In operation, the slurry is first pumped to the chambers between each two plates and all frames are filled. As more slurry is pumped, the pressure increases and the filtrate flows through the cloth, ending down to the drip tray. When the filtration is completed, the cake can be pressed and washed. The final filter cake is released by opening the plates, causing the cakes to drop on the conveyor, where the discharged cake is moved for further processing. [8]

The number of plates depends on the desired filtrate capacity and cake thickness, and the capacity can be easily lowered by blanking the extraneous frames. Plate and frame filters do not need much space, so they are also suitable for a small floor area. [8] Typical use is batch processing of solids forming either incompressible or moderately compressible filter cakes. Particle size range is 1–100 μm and feed concentration 1–30% w/w. [4]

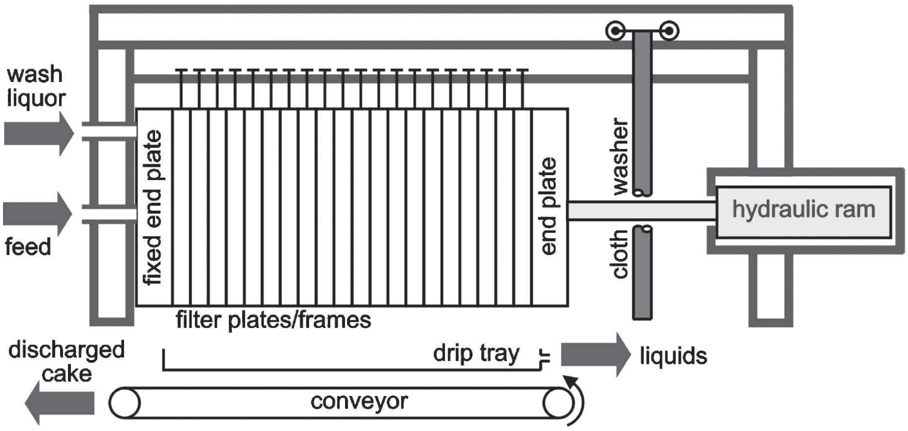


Figure 2.7 Vertical pressure filter [4]

2.4 Pre-treatment technologies

As introduced in Chapter 2.1, slurry pre-treatment is an important part of the filtration process. Pre-treatment is especially needed, when handling difficultly filterable slurries. By pre-treatment, the aim is to modify the properties which have notable effect on slurry filterability - the nature of the solid particles, the nature of the liquid and the interactions between the liquid and the particles [9]. These methods include heating the slurry, increasing the solids content and increasing particle size. Particle size can be affected by using additives or chemicals, which cause the particles to stick together. Also bulking the slurry with solid matter increases the particle size. [10]

Pre-treatment methods can be divided in chemical and physical methods, depending on which slurry properties the treatment is affecting. There are numerous of ways to perform pre-treatment for slurries, but the most widely used techniques are coagulation and flocculation, where flocculating and coagulating agents are added to the slurry to increase the particle sizes. Coagulation and flocculation are similar processes - they both include chemical addition to the slurry - but not synonyms with each other as they are frequently used. Coagulation means neutralizing electrical charges of the suspension, and flocculation aggregation between particles. Both methods are very common pre-treatment methods in filtration. In actual processes, often both coagulation and flocculation occur, but the dominant process is usually clear. Since chemicals are added in both situations, also the resulted filter cake includes these chemicals. In some processes, this might not be acceptable and have to be considered. Coagulation and flocculation are closely related to the interparticle forces for colloidal particles, which are presented more detailed in Ch. 3.3. [9]

In coagulation, the electrical charges can be neutralized by changing the nature and concentration of ions present. Coagulant refers to the chemical added to the suspension. In practice this can be done by adding an electrolyte of opposite charge than the particles have. Particles with repulsive forces do not aggregate easily, and by neutralizing charges the moving particles stick to each. The movement is made by Brownian motion, the random movement of colloidal particles. Aggregation is effected by reducing the electrical double layer repulsion between particles. For example in water treatment, in-organic salts have been used for a long time, but nowadays also long-chain organic polymers which contain cationic groups. [1]

Flocculation occurs when certain long-chain polymers or polyelectrolytes cause an aggregation between particles by forming bridges between them. Flocculant refers to the chemical added to a suspension to either accelerate the flocculation rate, or to strengthen the formed flocs. The flocculation is irreversible reaction unlike coagulation. [1] Increasing flocculant dose causes better flocculation up to the optimum point, but overdosing flocculant causes deterioration. Also many other different parameters have effect on flocculation process. For example increasing flocculant molecular weight causes poorer solubility and more viscous solutions, increasing particle surface area causes greater flocculant consumption and increasing particle concentration may cause smaller and perhaps stronger flocs, and may also cause local overdose. [4]

Beside coagulation and flocculation, also adding other filter aids is a common pre-treatment method. The filter aid can be used in two ways, either separately or in conjunction. In separate use, the filter medium is precoated with a filter aid cake, and after the aid is carefully filtered, the suspension is filtered by cake filtration mechanism, but also by depth filtration mechanism due to the cake formed by filter aid. The cake formed should have high porosity (0.85-0.90), low specific surface area, proper particle size distribution with non-uniform sized particles. [11]. In conjunction use, the filter aid is mixed with the suspension, and this combination of the two suspensions has different properties than the original one. The benefit can be attained in some cases, for example, by adding big particles and creating coarser size distribution, which opens up the filter cake pores and therefore increases filtration rate. Similarly with coagulation and flocculation, also adding filter aids causes the final product to include extraneous material. [1]

If chemical pretreatment is not possible or reasonable, there are still other physical methods, which can be considered. These methods are more seldom used, since majority of these methods represented are either expensive, or suitable for limited situations. Heating the suspension causes energy consumption to increase and therefore increases costs, but provides faster filtration by reducing viscosity. Combination of raised temperatures and pressures can have influence on particle-liquid interface, and therefore increase filtration rates. Also having changes in earlier stages, mainly when particles are formed, might have significant improvements. A process can be designed for easy filtration by modifying the earlier stages to create a slurry that filters optimally [10]. For example, a temperature gradient and the rate of cooling can have a great effect in particles, and therefore also in filtering properties. [4] A research by Kannangara et al. [12] showed, that with kraft lignin the hydrodynamics of the stirring tank had a great effect to the particle aggregation into lignin flocs. By manipulating the shear rate, the size distribution and shape of the final lignin flocs could be controlled.

Nevertheless, even a wide variety of pre-treatment technologies exist, their effect on slurry filterability has to be tested for each substance separately, and might be that the difference in filterability is negligible. In some cases even delicate pre-treatment don't have the desired outcome, and the filterability remains low. Then also checking alternatives for cake filtration have to be considered. [13]

3. THEORETICAL BACKGROUND OF FILTRATION

In order to model filtration, the most important slurry properties affecting on filtration rate have to be identified. In this chapter, these properties are defined, and their importance to overall filtration efficiency is investigated. The properties described are particle properties, nature of the fluid, particle interactions, filter media properties and filter cake properties.

3.1 Particle properties

3.1.1 Particle size distribution

Particle properties are one of the key factors affecting on filtration efficiency. Especially particle size distribution (PSD) has a major importance when determining different interactions. In general, increasing particle size indicates faster filtration rates and decreasing size slower filtration rates. For example with big, heavy and hydrofobic particles, separation with gravity settling might be enough. Instead, with colloidal particles gravity settling is negligible, and in the separation also interparticle forces have to be considered. [14]

Just measuring the mean particle size does not tell enough of the particle size distribution, since also the width of the size distribution is known to have effect on filterability. The basic rule of particle size distribution affecting on filtration is, that coarse particles with narrow size distributions give the best filtration efficiency. When particle size starts to decrease, or the size distribution gets wider, filtration slows down. These two sides are related to each other, since slurries with small particles also tend to have a wide size distribution [4]. Particle sizes can be divided in three different groups based on their size: coarse, fine and colloidal. In Table 3.1 these three types are defined according to the particle diamater. In the table is also effect of gravity settling in 20 °C water for these particle sizes. As seen from the table, separation using only gravitional settling is reasonable with coarse particles, but when the particle size decreases, the settling time increases. With fine or collidal particles, separation using gravity settling is not practically possible.

Table 3.1 *Particle size and gravity settling [1]*

Suspension	**Particle size (μm)**	**Time to settle 5 cm**
Coarse	100 - 1000	1 s - 13 s
Fine	1 - 100	13 s - 20 h
Colloidal	0.001 - 1	20 h - 2 a

Particle size depends on how it is measured. Different ways to measure particle sizes are for example by number, length, surface area or volume. Measuring the size by length is seldom used in practice, but the rest methods are quite common. Figure 3.1 shows the same particle size distribution is presented by these four different ways. Particle size distribution measured by number tend to highlight the small particles, while PSD from mass or volume distribution results to a more stable distribution. Conversion from one distribution to another is possibly with uniform particles. [6]

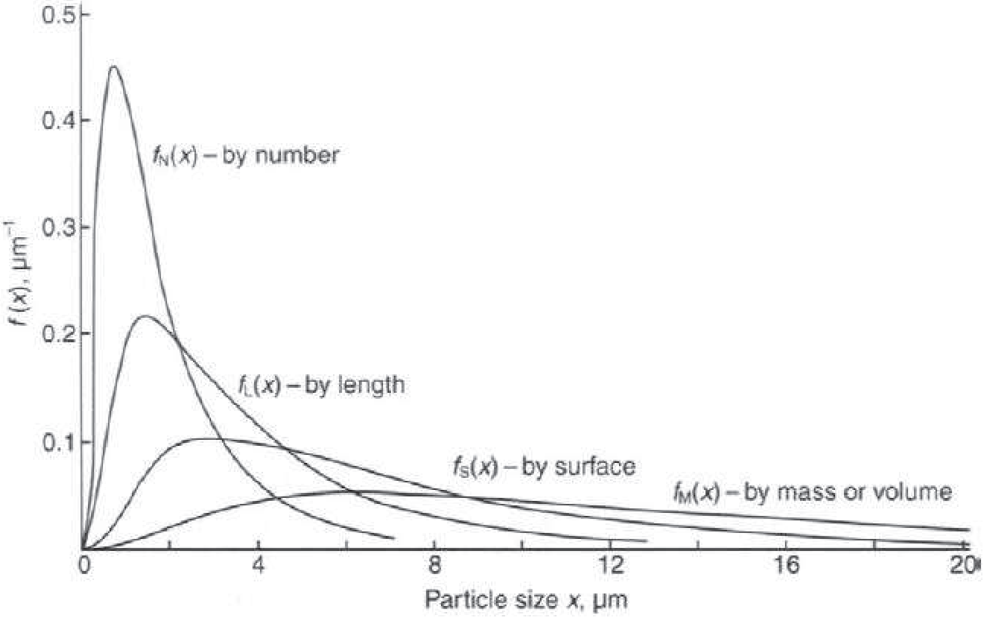


Figure 3.1 *Different particle sizes [6, p. 34]*

Particle size distribution is usually presented in visual form, but also mathematical methods to describe the PSD have been created, which can be useful, for example, with modeling. One way to describe the PSD is calculating the specific surface area (SSA), expressed as S_0. It is described as total surface area divided by volume ratio (A_p/V_p), usually expressed in form m^2/m^3 or m^{-1}. If spherical-shaped particles are assumed, the specific surface area can be calculated as

$$S_0 = \frac{6}{x_{sv}}, \tag{3.1}$$

where x_{sv} is Sauter diameter, the mean diameter of a particle size distribution. Sauter diameter can be calculated by dividing the total volume by the total surface of particles. As expressed in a single number, specific surface area is a practical way to describe the size distribution. With mono-shaped particles, decreasing particle size causes the specific surface area to increase. [1, 13]

The smallest particles produce most of the specific surface area, and the greater the SSA is, the slower is the filtration rate. Beside this, the smallest particles are difficult to filter due to several reasons. In the beginning of filtration, the smallest particles can bleed through the filter cloth and accumulate in the filter cake next to the medium. The smallest particles also interact with ions or other substances in the solution, which causes the compressibility effect. Hence, the smallest particles of the size distribution are the most important ones, since they control the filtration more than the bigger particles. If the amount of these fine particles increases even a bit, it does have a great effect to the whole filtration efficiency. Because of this, making calculations using the mean size is not always reasonable. Wakeman et al. [15] have suggested, that better way is to either use the 5 % or 10 % sizes from the PSD, or observe the whole size distribution to the calculations.

In addition to predict the filtration rate of a specific slurry, calculating the size distribution is valid. The size distribution can be measured with several different methods, for example by microscopic inspection, sieving, elutriation and sedimentation. With electron microscope, it is possible to measure particle sizes down to nanometer range. The most widespread technique is using laser diffraction-based equipment, size range 0.5 - 800 μm, because of their convenience. [1]

3.1.2 Particle shape

Particle shape is seldom an extremely important parameter affecting on filtration efficiency, compared to particle size distribution. Nevertheless there is also situations, when particle shape becomes decisive parameter affecting on cake properties, especially on cake compressibility which is explained in Ch. 3.5.3. The effect is great, particularly, with needle-shaped particles, and other particle shapes far from sphere. [16]

Particle shape is hard to define precisely, since solid particles are rarely spherical, or even uniform. Majority of solid particles have irregular shape, which differs with every particle. Fibrous particles are common, but also they differ within the same material by length, width, height and surface smoothness. Particle shape together with particle size affects to the specific surface area presented before. Fibrous particles have a lower specific surface area than the other shapes, and flakey or plate-like shape has the greatest specific surface area. This indicates that fibrous materials are the easiest to filter. Nevertheless, this is not always correct, since fibrous particles tend to pack to a lower porosity, which affects also to the cake resistance by increasing it. [2]

Many different methods describing particle shapes exist. One common method for defining particle shape is called sphericity (Ψ), which is defined as

$$\Psi = \frac{\text{surface area of sphere of same volume as particle}}{\text{surface area of particle}}, \tag{3.2}$$

where Ψ has a range from 0 to 1. Perfectly round particles have volume shape factor equal to 1. A great difference between length, width and thickness indicate a small shape factor, and equal length, width and thickness indicates shape factor near 1. In Table 3.2 are some values of volume shape factors for various shapes. [1]

Table 3.2 *Volume shape factors for known shapes [1, p. 492]*

Shape	**Sphericity**
Rounded particles	0.82
Angular particles	0.66
Flaky particles	0.54
Thin flaky particles	0.22

Shape characterization can also be done by using shape factors, which can be created by comparison of different particle diameter ratios. Many different definitions of shape factors can be found from the literature, for example describing particle slimness or concavities. M. Oja [17] investigated shape characterization for mineral slurries, and came to a conclusion that exact particle shape can not be defined by using only one shape factor. Oja suggested, that if exact information of particle shape is needed, several shape factors should be used.

3.1.3 Particle structure

With majority of slurries, eg. mineral slurries, the particles have a rigid structure. However, with biomass based slurries, the particles might be soft, and therefore deformable. The particle deformability might have an enormous effect on slurry filterability, and therefore especially with biomass based slurries the deformability have to included, when slurry filterability is predicted.

Research by Hinge and Christensen [18] investigated how small, non-charged and water-swollen particles affect on filtration. This material, made from synthetized core-shell particles, formed a gel layer which increased the specific cake resistance. With only a small amount of gel, the gel deformed and filled some parts of the cake voids, increasing the cake resistance. When the amount of gel was increased, the gel filled the cake voids entirely and increased the specific cake resistance, so that the resistance was straightly connected with the gel permeability.

Also another research by Mattson et al [19] investigated blinding effect on filtration. In their research, the focus was on a skin formation, which refers to a layer of higher specific resistance inside a cake. This skin formation increases the overall resistance, and is therefore harmful for the filtration rate. The used material was micro-crystalline cellulose and the variables filter medium, pressure and pH. The research founded, the in this case the filtration resistance was highly depending on the used filter medium - more than one order of magnitude. Decreasing suspension pH lowered the resistance. Also the great differences between different filter medias decreased. Charasterization between the filter media and the suspension indicated, that the reason was that a skin layer was formed in the filter cake closest to the filter medium, not the filter media clogging.

The solvent-swollen materials in organic suspensions is also an important factor influencing the filtration properties, and has been investigated. [20] Solvent-swollen materials might explain the nonlinear increase in filtrate volume, which has been measured for some substances. Unlike mineral particle suspensions, majority of organic particle suspensions may contain solvent-swollen particles, which means the particles have soft and deformable structure. During compression, filter cakes do not form only because of particle rearrangement, like with inorganic material, but also because individual particles deform. These deformable materials might fill up the voids between particles, which causes high cake resistance values. Also another research investigated filtration of organic water-swollen particles with dense core and gel-like shell [21]. In the investigation, different particles with different shell-core ratios and particle sizes were filtered. As a result, the investigators found that the shell volume fraction had more effect to the specific cake resistance than the particle size, and the compressibility was depending on the shell volume fraction linearly. Based on these two investigations, it seems that the solvent-swollen, deformable particles do have a effect on filterability, compared to similar particles with a dense structure.

With deformable particles, increasing the filterability might be possible by modifying the particle softness. This is possible by having changes in temperature - colder environment might make the particle structure more rigid. With these particles, cooling the slurry before filtration could be an advantage, if the changes in the particle structure outweigh the effect of increasing viscosity. [10]

3.2 Nature of the fluid

The particles and the fluid interface in many ways. The most important fluid properties affecting on filtration efficiency are viscosity and density, but also other gradients, such as solids concentration, are important. The greatest effect of the fluid properties is made by viscosity.

The importance of viscosity to filtrate flux can be seen from the basic filtration calculations (see Ch. 4.1.1), where the rate of filtrate is inversely proportional to the liquid viscosity - if viscosity is halved, the filtrate flow is doubled. The effect of viscosity is one [9]. Fortunately, it is rather easy to modify the viscosity, since viscosity is usually sensitive to changes of temperature. With liquids, increasing temperature causes a decrease in viscosity. It should be noted, that the same benefit is not obtainable with gases as their viscosity increases as the temperature is raised.

For highly viscous non-Newtonian liquids even a small temperature change can affect viscosity greatly. Using higher temperatures in order to obtain a drop in viscosity can cause other good benefits if the filtration cycle is continued with liquid washing; a hot feed may leave hot liquid in the pores of the cake prior to deliquoring, which makes deliquoring more rapid and may also lead to lower cake moisture contents. Beside by changing temperature, liquid viscosity can be effected also by diluting the slurry with a liquid that has lower viscosity value. Changing the viscosity rate by adjustment the temperature is more used and an easier way to control the viscosity, but in some cases, diluting the slurry with another liquid might be beneficial. Careful dilution offers increased flow rate, but carefulness is insist, so the total excessive volume will not eliminate the benefit. [1, 2]

The importance of density depends on the used equipment, and it has a significant role on the filtration efficiency when the separation process depends on it. Such devices are, for example, thickeners or centrifugal sedimenters. The density difference between the liquid and particle cause sedimentation with coarse particles, which helps the separation. In cake filtration density has practically a negligible role. Density is also hard to modify, so usually it must just be accepted. If the density have to be controlled, the methods are mostly the same as when changing the viscosity: density can be changed by temperature change or by diluting it with other substance that has lower density. Unlike the viscosity, which depends greatly on temperature, density depends on temperature only a slightly. Also diluting the slurry with a liquid with lower density is seldom a good choice. One possibility to effect on the density is by ageing or by chemical changes. [2, 9]

3.3 Particle interactions

Particulate interactions with other particles and surrounding fluid have negligible role with coarse particles, but are extremely important with colloids. With those small-sized particles, electrical charges become more meaningful. The interactions between particles are explained by introducing theory considering colloidal stability by Derjaguin, Landau, Verwey and Overbeek (DLVO), and Zeta-potential, which is describing electrokinetic potential of particles.

3.3.1 DLVO theory

Theory by Derjaguin, Landau, Verwey and Overbeek, usually expressed as DLVO theory, explains interactions between colloidal particles and their aggregation behavior. The assumptions in the theory are, that the repulsive and attractive forces occur only due van der Waal's and Double layer forces. The affecting force is the superposition of these two forces. [13]

Attraction is caused by van der Waal's force, which is a force occuring between atoms and molecules, and depends on the distance between them. The force results from interactions of the rotating dipoles of atoms and molecules, and are almost always present. In most situations the van der Waal's force is attractive, but repulsive force is also possible. The range how far the force affects is smaller than with electrostatic charges. The greatest effect of van der Waal's forces is when the particle distance approaches to zero. When the distance between particles increases, the interaction falls apart quickly. Rough surface might decrease this interaction also at small distances. Repulsion is made by electrostatic charges, double layer interactions. Particles in a suspension have a electrically charged surface, because of existing ions which adsorbs and dissolves in the substance. The repulsion forces depend on the liquid pH. The area this charge reaches, depends on the ion content of the surrounding liquid, but is typically quite far compared to the van der Waals's forces. [22]

The superposition of these two forces is the basis of DLVO theory. In Figure 3.2 is an example of Wan der Waal's and double layer forces together with the superposition of these two in different distances, when assuming two identical colloid particles. When the distance is extremely small, the total net force is attractive. At the medium distance, net force becomes repulsive, and in long distance, the force becomes to zero. If the energy profile is repulsive, the particles reject each other, and when the energy profile is attractive, the particles stick to each other. Repulsive forces create a suspension that can said to be stable, when attractive forces create an unstable suspension. In stable suspension particles held each other, while in unstable suspension particles aggregate with each other. When the aggregation has been taken a place for a while, the formed agglomerates might become big enough to cause sedimentation in the suspension. [22]

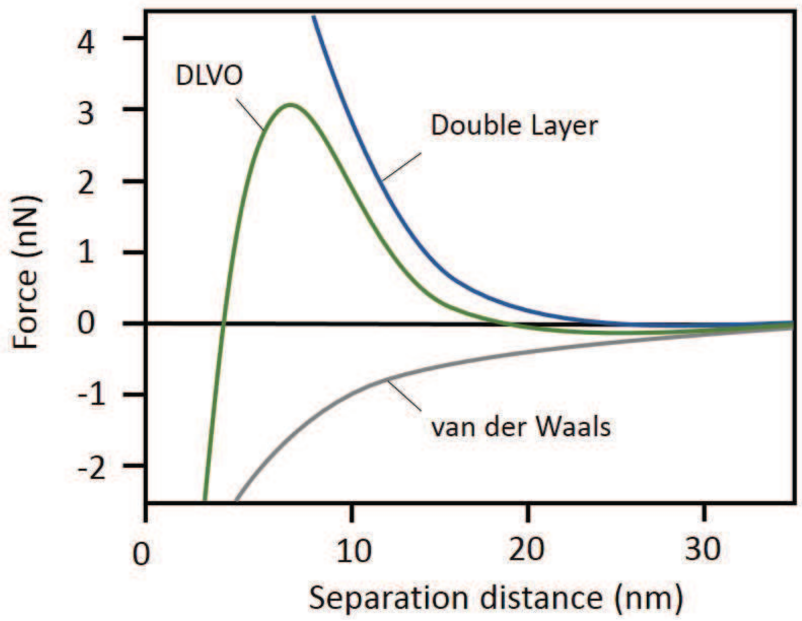


Figure 3.2 DLVO theory [22]

3.3.2 Zeta-potential

The surface charge can be measured by zeta-potential, also called as electrokinetic potential. Zeta-potential expresses net repulsive forces between particles, and therefore the stability of the slurries. The stability affect mainly to the flocculation behavior, which affect greatly on filterability. [23]

Zeta-potential can be measured by using several different techniques. The most common method is using ultramicroscopic techniques, where a dilute suspension is in a cell, which consist thin glass tube, which is charged. The solution has electro-osmotic flow, where the particle velocity and total velocity can be calculated. Another common method is laser velocimetry technique, where scattered light show fluctuation in intensity. This fluctuation is caused from Brownian motion, random movement of small particles, and the method is therefore suitable for only particles small enough affected by the motion. The time from intensity maximum and minimum is approximately the same, when particle move one wavelength, and Zeta-potential can be calculated from the intensity data. [24]

Slurry pH is an decisive parameter affecting on Zeta-potential, especially in aqueous dispersions. Suspensions with high pH have high concentration of OH- ions and negative surface charge, and suspensions with low pH high concentration of protons and a positive surface charge. The surface charge is neutral in some point between the high or low pH, and this point, where Zeta-potential is equal to 0 mV, is called the isoelectric point. In the isoelectric point the filtration has

(a) Faster particle settling
(b) More rapid cake formation
(c) A bit higer moisture content in cakes

compared to a situation, where Zeta-potential is at the maximum or minimum point. At the maximum or minimum point the consequence is the opposite: the settling rates and filtration slows down, but the cake is slightly drier. The reason why the filtration is faster near the isoelectric point is caused by colloid stability. Close to isoelectric point colloids lose stability and tend to agglomerate or flocculate, and therefore create bigger particles. For fast filtration it might be worthwhile to determine the isoelectric point, though the optimal pH is often determined empirically without knowledge of the actual value of Zeta-potential. [15, 25, 13] Also beneficial effects in the rest of the filtration cycle are possible: the deliquoring and washing rates may also be faster near to the isoelectric point [2].

Beside changes in pH, also changes in ionic strength and consentration have influence on Zeta-potential [25]. With increasing ionic strength, the zeta-potential decreases and vice versa. This is caused because of the electrical double layer becomes more compressed. With changes in concentration, the relation is more complicated. To simplify, in dilute conditions zeta-potential increases with increasing concentration due to the surface adsorption phenomenon, which dominates the forces. With high concentrations, zeta-potential decreases with increasing consentration, since the electrical double layer thickness dominates the process. [25] Zeta-potential and repulsive forces increase when the solids volume fraction in the mixture increases. Reducing the zeta-potential causes unstable dispersion which can be separated more easily. Zeta-potential can be reduced in two ways. The first way is by adding a non-absorbing electrolyte to the liquid, and the second is by altering the particle's electrical charge by adsorption of certain ions or charged polymers. [15]

Zeta-potential have also noticed to have wider effects on cake properties, such as porosity and compressibility. A research [14] with TiO_2 particles with varying zeta-potential showed, that the cake compressibility could be varied by altering the zeta-potential. The reason behind the behavior is not clear, but possible explanation is different stability of agglomerates with different zeta-potential values. The weak agglomerates with high pH break during filtration, causing a more compressible cake compared to strong agglomerates.

3.4 Filter media properties

The filter media causes a separation between particles and liquid by being permeable for liquid, and non-permeable for particles. This causes liquid flow through filter medium, while particles stay stuck on the media. Having changes in the filter media is the easiest way to affect on the filtration performance, but also the most critical part in filter design. A wide variety of filter medias made from different materials are available, for example containing filter medium made of metal sheets, fibers, ceramics, or wires. [9]

The selection of most suitable filter media for a certain process has many aspects that have to be considered. These aspects include especially the permeability of the clean filter media, permeability for used media and the particle retention capability. The permeability of a new and used media may have a great variation, because in some cases particles blind or plug the pores in the media, causing slower filtration rates and shorter lifetime of the media. The permeability and particle retention power depends mainly on the media structure but also the interactions between particles and the medium do effect. [4] In successful cloth selection many different aspects have to be considered. In a correct cloth selection the following benefits should occur:

(a) Clear filtrate
(b) Good cake release
(c) High filtration capacity
(d) Absence of media blinding
(e) Long cloth lifetime

In practice, this list of requirements is much longer. Also requirements for example considering construction and fitting side [1] and chemical and thermal stability in different process conditions has to be included.

Woven fabrics is the most commonly used group of filter media in cake filtration for both pressure and vacuum filtration. When describing a woven fabric, the nature of the used fiber is the most obvious variable. The cloth can be made from natural fibers such as cotton, or from synthetic fibers such as nylon. A simple way to divide woven fabrics into different groups are by the media construction. Different yarns can be divided in three different forms, which are staple fibers, monofilaments and multifilaments. Natural fibres such as wool and cotton occur in shorth lengths, and they are spun into stable yarns. Monofilament fibers are single filament strands, which can be woven directly into fabrics. Multifilament fibers are a bundle of filaments twisted together, which makes the yarn heavier. These yarn types all have their own strengths and weaknesses when describing filtration. These properties are summarised in Table 3.3. [9]

***Table* 3.3** *Effect of type of yarn on cloth performance in decreasing order [9, p. 69]*

Maximum filtrate clarity	**Minimum resistance to flow**	**Minimum moisture in cake**	**Easiest cake discarge**	**Maximum cloth life**	**Least tendency to blind**
Staple	Monofill	Monofill	Monofill	Staple	Monofill
Multifil	Multifil	Multifil	Multifil	Multifil	Multifil
Monofill	Staple	Staple	Staple	Monofill	Staple

Beside the material aspects, also the weaving structure has a great effect on cloth performance. Fig. 3.3 illustrates different fabric filter cloths made from same material, but different weaving type. The represented weaves are plain, twill and satin. [9]

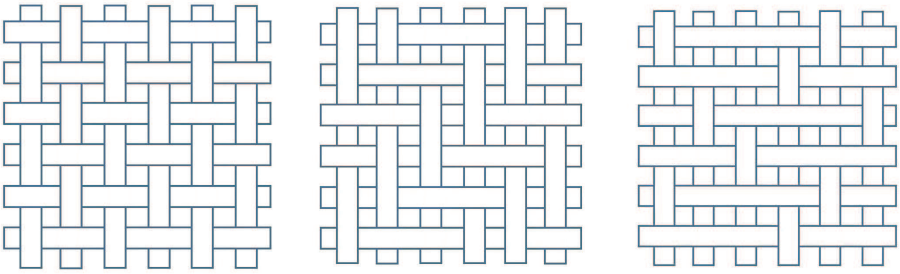

(a) Plain (b) Twill (c) Satin

***Figure* 3.3** *Three basic weave types [9]*

Even though these cloths are made from the same material, their filtration properties differ by the weaving structure. These effects of the properties caused by weaving type are represented in Table 3.4 by comparing maximum filtrate clarity, resistance to flow, cake moisture and discharge, cloth lifetime and tendency to blind. As seen from the table, the filter cloth choice criteria cannot only be based on cloth resistance or permeability. Depending on the process, also gradients like cake discharge, cloth life or tendency to blind can have a significant role in cloth criteria.

Table 3.4 *Effect of weave pattern on cloth performance in decreasing order [9, p. 71]*

Maximum filtrate clarity	**Minimum resistance to flow**	**Minimum moisture in cake**	**Easiest cake discarge**	**Maximum cloth life**	**Least tendency to blind**
Plain	Satin	Satin	Satin	Twill	Satin
Twill	Twill	Twill	Twill	Plain	Twill
Satin	Plain	Plain	Plain	Satin	Plain

Filter media properties are usually expressed by porosity or permeablilty. Permeability (μ) is described as the rate at which gas diffuses through a certain surface. Within filtration, it is usually expressed as under a constant pressure differential (eg. m3/s*m2 at 200 Pa). Porosity (ϵ) is described as free space of a fabric, usually expressed in percentages. The resistance of a porous media depends on the number of pores in the media, and on the sizes of each pore. A media with a great amount of finest possible pores would be ideal, but in practice, the holes are located only a relatively small area on the surface. Porosity and permeability relate strongly with each other, since high permeability is often an indication of high porosity. [1, 9] When adapting filter media properties to the filtration models, filter media is commonly described just as by media resistance R_m [1/m]. [6]

3.5 Filter cake properties

Filter cake formes during filtration by particles stuck on the medium. In the early stages at filtration, the cake is not formed yet and some particles flow through the medium with filtrate. As filtration continues, filter cake starts to form and it becomes remarkable part of the process. Prediction of cake properties is extremely important part of designing filtration process, since how the filtration succeeds, depends mainly on the cake properties [13]. Filter cake properties represented are resistance, compressibility and porosity. All these three are closely related to each other, but the resistance of the filter cake is most important parameter.

3.5.1 Resistance

Filter cake resistance is defined as the resistance, which occurs when fluid flows through the cake, and is used for comparing the filterability with different slurries. Cake resistance is usually calculated from experimental data, since it is hard to predict especially with small particle slurries. An accurate method of estimating cake resistance would also give good estimates of filtration rate, since by using cake resistance together with liquid viscosity, pressure difference and the filtration area the filtrate flow rate can be calculated.

The filter cake resistance can be expressed in two ways. The first way is by cake resistance R_c [1/m], which describes the total cake resistance and increases together as the cake is formed and the cake thickness increases. The second way is by cake specific resistance α [m/kg], which is a constant during filtration for incompressible cakes. Figure 3.4 shows mathematical expression for these two resistances. [7]

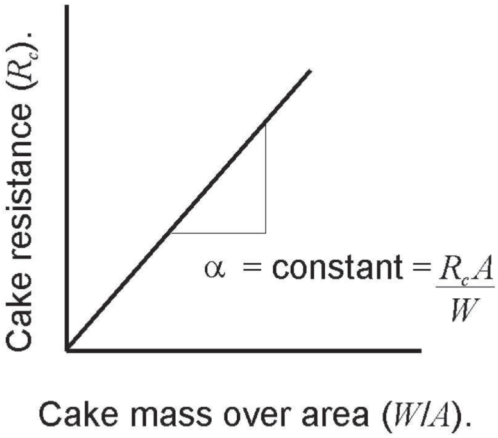


***Figure** 3.4 Cake resistance [7]*

The specific cake resistance is used for comparing the filtration resistances with different suspensions. Cake resistance R_c increases linearly when cake mass over area increases, and the specific cake resistance α can be calculated from the slope. High specific cake resistance indicates difficult separation, and low specific resistance easy separation. High resistance values are typical especially for sludge-like material [1]. Wakeman et al. [2] presented characterization of separation easiness. Separation is easy, when cake resistance is below 1×10^9 m/kg, and very difficult when the resistance is more than 1×10^{13} m/kg. This is presented in Table 3.5. Nevertheless, the Table 3.5 gives quite simply way to determinate the ease of separation, since the actual easiness cannot be defined only with knowledge of cake resistance - also filter cloth resistance have effect to the total resistance. At high levels of α, e.g. greater than 1×10^{12} m/kg, filter cake resistance tend to control the overall resistance. In this case, changes in filter cloth resistance R_m have only a little influence in overall efficiency, especially when $1 \times 10^8 < R_m < 1 \times 10^{11}$. [2]

Table 3.5 *Ease of separation [2, p. 116]*

Ease of separation	α_{av} **(m/kg)**
Very easy	$< 10^9$
Easy	10^{10}
Moderate	10^{11}
Difficult	10^{12}
Very difficult	$> 10^{13}$

As mentioned in Ch. 3.1.1, specific resistance is greatly affected by particle size, since smaller particles usually create a more compact cake. Also cake porosity, which depends mainly how particles are packed to the cake, affect greatly to the cake resistance. In Table 3.6 the effect on particle size and cake porosity in specific cake resistance for a certain suspencion is showed. [2]

Table 3.6 *Effect on particle size and porosity on the cake specific resistance [2]*

Particle size (mm)	**Porosity** (ϵ)	**Specific resistance** (α)
1	0.4	6.7×10^{11}
2	0.4	1.7×10^{11}
10	0.4	6.7×10^9
100	0.4	6.7×10^7
2	0.4	16.9×10^{10}
2	0.5	7.2×10^{10}
2	0.6	3.3×10^{10}
2	0.7	1.6×10^{10}

Cake specific resistance depends on many factors presented before - such as particle shape and size, applied pressure, other particle properties, cloth properties, and particle-particle and particle-medium interactions. Cake resistance is closely related to the other cake properties, such as cake permeability and porosity. [26] The wide variety of affecting variables make the prediction of cake specific resistance difficult. Polydisperce particle size distributions, variation in particle shape, and presence of electrical charges make the modeling even more complicated. Notable is also that the cake starts to form in the beginning of the filtration, which means that before the cake starts to form, some particles have already likely passed the filter media. This causes the PSD in the cake is different from the PSD from the actual slurry. [27]

An accurate prediction of cake resistance from slurry properties have not been created. Some models for linking the cake resistance with particle properties and cake porosity do exist, but they are based on Kozeny-Carman equation (see Ch. 3.5.2), and are therefore only valid for big, $>100\ \mu$m particles. Specific cake resistance can be calculated as

$$\alpha = \frac{180}{\rho_p d_{vg}^2} \frac{(1-\epsilon)}{\epsilon^3}, \tag{3.3}$$

where d_{vg} is particle size, ρ_p particle density and ϵ cake porosity. The model has been modified by many investigators. Eq. 3.4 presents a model created by Endo et al. [28] for calculating the specific cake resistance. It is based on Kozeny-Carman equation but is modified by adding dynamic shape factor and the geometric standard deviation to the calculations.

$$\alpha = \frac{180}{\rho_p} \frac{\kappa}{d_{vg}^2 exp(4ln^2\sigma_g)} \frac{(1-\epsilon)}{\epsilon^3} \tag{3.4}$$

where κ is dynamic shape factor and σ_g geometric standard deviation of a size distribution. This equation also needs some experimental data or rough assumptions to be used, since a reliable method for assuming cake porosity from particle data have not be created.

Even though few models predicting cake specific resistance from slurry characteristics have been created, they are all suitable for limited situations, and typically for coarse particles. An useful model to predict filterability for slurries consisting small particles have not been created, and therefore determining filterability experiments have to be made. M. Arora [29] stated in his dissertation published in 1970 that "the filtration process is so complicated that it looks impossible that a design engineer will ever have a mathematical formula at his disposal that would be applicable in all situations". Also some researchers, such as Foley [30] investing microbial suspensions, stated that experiments for estimating slurry filterability are still needed, since specific cake resistance is extremely hard to predict.

3.5.2 Permeability and porosity

Permeability and porosity are commonly used to describe the cake properties. Both characteristics were briefly introduced for filter media, but are presented more detailed in this chapter. Permeability and porosity are closely related to each other and to cake resistance, and are therefore important parameters when evaluating slurry filterability.

When evaluating cake properties, porosity ϵ describes the amount of free space in the cake. Porosity can be calculated as the volume of voids divided by the total bed volume, and therefore describes the volume where the liquid is free to flow. High porosity indicates low specific resistance, and low porosity high specific cake resistance. Another way to describe the cake porosity is solidosity ϕ, which is the opposite of porosity - amount of solids in a filter cake. It can be calculated from dividing volume of particles by total cake volume. High solidosity indicates high specific cake resistance. [1] Both values can be also calculated, if the other one is known, using equation

$$\epsilon + \phi = 1 \tag{3.5}$$

since the total cake volume is the sum of the solid matter and the pores in the cake. Both units, porosity and solidosity, have a range from 0 to 1. [31]

Local solidosity can be measured by dissectioning the cake, and measuring the solidosity of different sections by drying them separately. This is an easy was, but also equipments for measuring local solidosity have been invented if more accuracy is needed. The measurements of the local solidosity have proven that the cake solidosity varies during filtration, and varies also in different cake depths. Local solidosity is greater near filter cloth, and lower on top of the cake. Since cake resistance is depending closely on cake porosity, the information of local solidosity in the filter cake can give valuable information of the filterability in different cake layers, when exact information is needed. Nevertheless, in the basic calculations average solidosity of the filter cake is used. [32]

Permeability k characterizes the easiness of a liquid flow through the cake and media. Permeability is greatly affected by cake porosity, and furthermore particle size distribution. Instead, slurry concentration and filtrate flow rate do not affect to the permeability. The Kozeny-Carman formula is at the moment the most used empirical model for predicting permeability. [27] In the formula, permeability can be expressed as

$$k = \frac{\epsilon^3}{K(1-\epsilon)^2 S_0^2}, \tag{3.6}$$

where K is the Kozeny constant, which is a slurry-specific constant. The value of K is typically 5 for slowly moving beds and 3.35 for rapidly moving beds. S_0 is the specific surface area presented in Ch. 3.1.1. [1] The equation can be modified to express the filtrate flow, and it is explained further in Ch. 4.1.3.

3.5.3 Compressibility

Cake compressibility explains how cake properties - resistance, porosity and permeability - change when the cake is under a certain pressure level. Conventional mathematical models are mainly designed for incompressible cakes, which means that the cake's properties are assumed to remain constant with different pressure levels. With some slurries, this assumption is valid, and the cake properties do remain constant even the pressure is increased. But with some other slurries, the effect of different pressures is remarkable, and the effect of compressibility have to be added to the calculations. It is crucial to determine the compressibility when the most suitable solid–liquid separation method need to be defined, since the compressibility have a notably effect in filterability with certain slurries. [16]

Typically particle slurries with large particles (> 50 μm) create an incompressible filter cake, and particle slurries with small particles create a compressible filter cake. With compressible cakes, the cake's properties tend to depend on the applied pressure. It should be noted that even the particle size distribution has a great effect on slurry compressibility, it is not a decisive parameter determining it - cake compressibility depends much wider on the physicochemical properties of the particle slurry. [2] Beside on particle size, compressibility depends also on the chemical composition of the particle. Compressibility is typical for especially organic slurries, though inorganic particle slurries can also form a compressible filter cake. With inorganic particles, the compression happens due small particle rearrangement. With organic particles that are soft or deformable, compression can form a compact cake with a great specific resistance value even at small pressure levels. [33]

The compressibility can be described by compressibility index n. When n has a value near 0, the cake is incompressible, with value 0.5 slightly compressible and with value around or above 1 the cake is very compressible. In most cases the value of n is measured from experimental data [2]. If the compressibility factor n and the cake specific resistance α in a certain pressure is known, the values of specific resistance with another pressure difference Δp can be calculated as

$$\alpha = \alpha_0 (\frac{\Delta P}{\Delta P_0})^n, \tag{3.7}$$

where α_0 is the cake specific resistance with pressure difference Δp_0. In the same way, the cake porosity can be calculated as

$$\epsilon = \epsilon_0 (\frac{\Delta P}{\Delta P_0})^\beta, \tag{3.8}$$

where same way as in the Eq. 3.7, also in Eq. 3.8 the unit ϵ_0 is the value of porosity with pressure difference P_0, and β is an empirical coefficient. [2].

With very compressible cakes, filtration time can not be reduced by pressure increase, which works for incompressible filter cakes. With compressible cakes the specific cake resistance increases proportionally with pressure, making the flux remaining the same or even creating a cake with very high specific resistance value, which causes the flux slow down. Cake compression is typical when filtering soft particles. In Figure 3.5 the difference between incompressive, moderately compressible and highly compressible structure is shown. In Figure 3.5(a) the inverse specific resistance is expressed as a function of structure stress. Inverse local specific resistance remains constant with increasing stress, while with moderately or highly compressible structure the specific resistance increases (inverse resistance decreases) with increasing stress. In Figure 3.5(b) the filtrate flow rate is represented to the same structures. With incompressible structure, the flow rate increases proportionally as a function of applied pressure drop, while with highly compressible structure the filtrate rate stops at the critical pressure. [33]

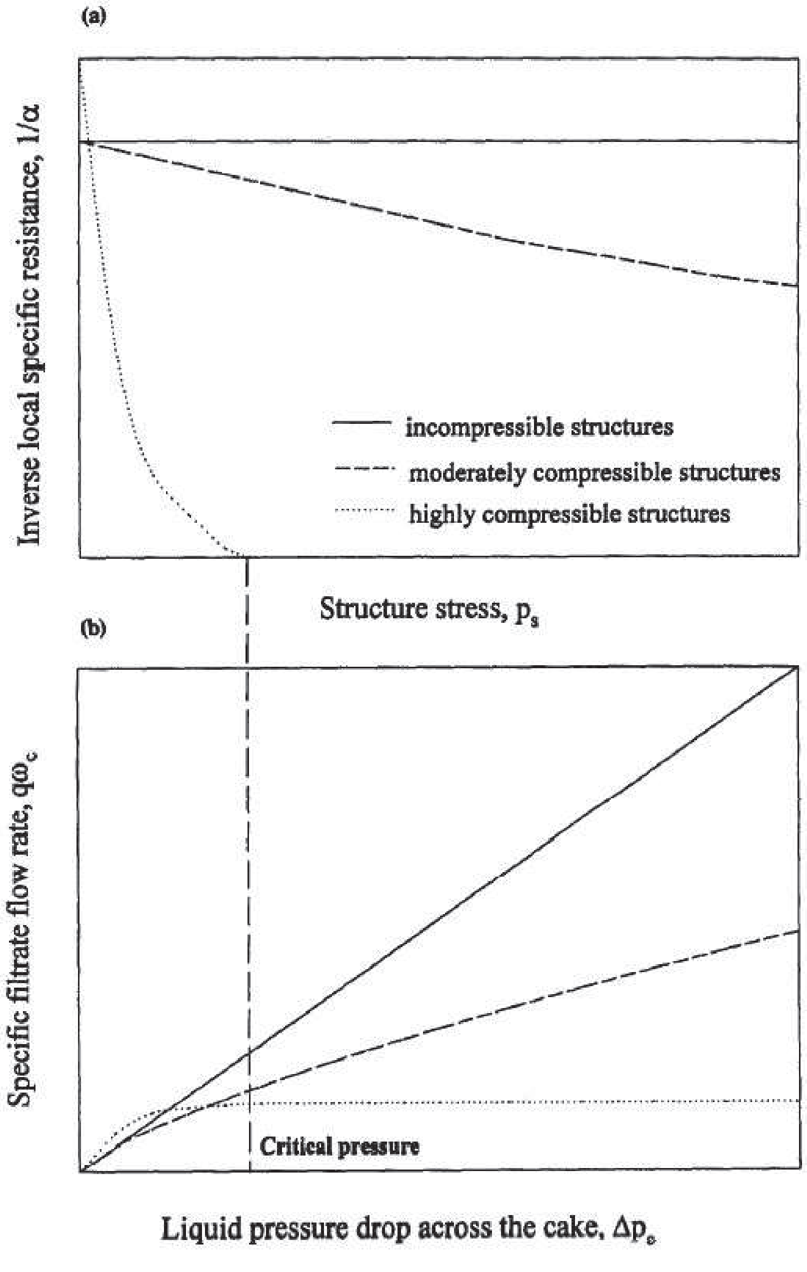


***Figure* 3.5** *Compressive filtration [33]*

As most of the cake properties, also compressibility factor is usually defined experimentally. Nevertheless, models predicting compressibility have also been created. The compressibility factor is known to be dependent on amount of organic matter in slurry, but also cake porosity, mean particle size and the extent of the size distribution do affect on cake compressibility. [2] Properties as pH, particle shape and particle-particle interactions are also reported to have effect on cake compressibility. [34] Also changes in zeta-potential [14] have been reported to affect on compressibility, as stated in Ch. 3.3.2.

4. FLUID FLOW THROUGH THE CAKE

In this chapter, equations describing filterability are introduced. Numerous different models have been invented, most of them being suitable just for limited applications. The first wide-known theory to describe filtrate flow through a porous medium was Darcy's law. After that Ruth's et al. conventional filtration theory was invented, and it soon became common equation in filter design. Also more recently new filtration models have been created.

4.1 Conventional models

4.1.1 Darcy's law

Darcy's law was created in the middle of 19th century by Henry Darcy. It was developed originally to describe the flow of water through porous sand bed, but it became soon a basic equation to describe also a flow through a filter cake. Darcy's law is formally is a force-momentum balance. The main discovery Darcy had, was that the pressure drop through the cake is directly propotional to the flow through the media. [2] The equation is written as

$$Q = \frac{A\Delta P}{\mu(R_m + R_c)}, \tag{4.1}$$

when the resistances against liquid flow are the filter media resistance R_m and the cake resistance R_c. Liquid velocity through the cake (filtration rate) is marked as Q [m/s], the liquid viscosity as μ [Pa s] and the pressure drop ΔP [kPa]. In the beginning of filtration, the cake hasn't formed yet so R_c is equal to 0. When the filtration goes further, R_c increases as the cake height increases, and is therefore a time-depending unit. R_m is usually assumed as a constant, through particle blinding might increase the actual media resistance. [6]

The cake resistance R_c can also be described as

$$R_c = \alpha w, \tag{4.2}$$

where α is the cake specific resistance [m/kg], and w [kg/m^2] is the mass of a cake per unit area. For incompressible cakes, α is a constant. Combining the equations lead to

$$Q = \frac{A\Delta P}{\mu\alpha w + \mu R_m}, \tag{4.3}$$

which is a basic filtration flow rate equation. The received cake per unit area is a function of time, and is related to the cumulative volume of filtrate. In Eq. 4.4 the mass of cake per unit area is expressed as

$$wA = cV, \tag{4.4}$$

where c is the solids concentration in the suspension, mass of solids per unit volume of filtrate [kg/m^3]. [6] The amount of dry cake received per filtrate volume can be calculated from slurry concentration, liquid viscosity and moisture ratio of the cake, using Eq. 4.5.

$$c = \frac{s\rho}{(1 - sm)}, \tag{4.5}$$

where s is the slurry concentration as mass fraction [w/w], ρ liquid density [kg/m^3] and m moisture ratio of the cake [-], calculated by mass of wet cake divided by mass of dry cake. [1]

4.1.2 Conventional cake filtration theory

Conventional cake filtration theory was originally developed by Ruth [35, 36] as early as 1935. It have been later modified by many different investigators, such as Grace [37], Tiller [38], and more recently by Tien and Bai [39]. It is often cited when cake filtration parameters are calculated, and the theory is said to be pioneering in the field of cake filtration [40]. The basics or Ruth's work are based on analogy with Ohm's law. The two resistances - filter medium resistance and specific cake resistance - are summed made the total filtration resistance:

$$\frac{d}{dt} = (\frac{\Delta P A^2}{\mu \alpha_{av} v})\frac{1}{V} + \frac{\Delta P A}{\mu R_m}, \tag{4.6}$$

where ΔP is the total pressure drop trough the cake and filter medium, V the volume of filtrate, μ is the liquid viscosity, A cross-sectional area of the filter, v cake collected per volume of filtrate, α_{av} the average cake resistance expressed in m^{-2} and R_m filter medium resistance expressed in m^{-1}. Ruth's model is widely-used model to calculate cake specific resistance from filtration data. The resistance can be calculated by plotting the previous equation with coordinates t/V against V. Cake spesific resistance α_{av} can be calculated from the slope, and R_m is the coordination of origin. [40] In case of constant pressure, the equation can be expressed in form

$$\frac{t}{V} = \frac{\mu \alpha_{av} v}{\Delta P A^2} V + \frac{\mu R_m}{\Delta P A}, \tag{4.7}$$

which is a common equation used in process design. From laboratory experiments, the cake spesific resistance is possible to calculate plotting t/V against V, which is represented in Figure 4.1. The resistance of the filter media can be calculated form the point where V is zero, and the resistance of the cake from the slope. This requires that the other properties are known. The figure shows also the expression part, where the linearity ends.

Cloth resistance can be calculated from the intercept. The equation for cloth resistance, calculated from the volume slope, is

$$R_m = \frac{B \Delta P A}{\mu_l}, \tag{4.8}$$

where B is the value of the intercept. Similarly, cake resistance can be calculated from

$$\alpha_{av} = \frac{K_s \Delta P A^2}{\mu v}, \tag{4.9}$$

where K_s is the value from the slope.

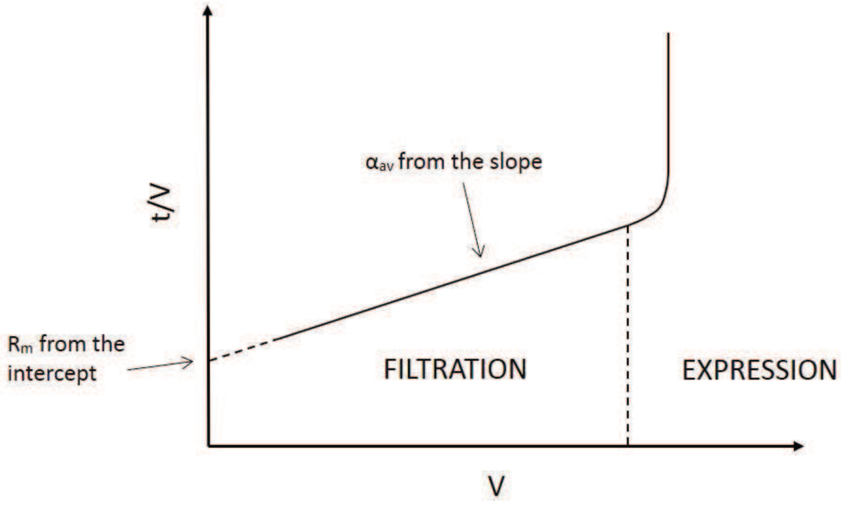


Figure 4.1 *Filtration and expression curve*

The biggest weakness in Ruth's model is, that it is working well only for incompressible or barely compressible materials. Also it does not include the cake properties (permeability or porosity) in the calculations. [40]

4.1.3 Kozeny-Carman equation

The Kozeny equation for calculating the permeability from porosity and particle specific surface was presented in Ch. 3.5.2. By substituting the permeability equation together with Darcy's law, created the Kozeny-Carman equation. If the filtrate volume is known the specific surface area can also be calculated from the permeability data. Filtrate flux can be calculated as

$$u = \frac{\epsilon^3}{5\mu S_0^2(1-\epsilon)^2\alpha}\frac{dp}{L}, \tag{4.10}$$

where ϵ is porosity.

Kozeny–Carman model has been found to give good specific resistance predictions for inorganic and uncharged suspensions. Nevertheless, it has been found to have several weaknesses. These weaknesses have been reported at with wide size distributions, spherical particles [2], biological suspension and activated sludge. In the Kozeny-Carman equation the particles are assumed to be rigid, in a fixed geometry and in a contact with each other. Because of this, the Kozeny-Carman equation is not accurate with small particles [1]. Also the complication of determining S_0 and ϵ is also a disadvantage of usefulness of Kozeny-Carman equation. Despite of these weaknesses, Kozeny-Carman is one of the basic models that is known to work for certain applications. It has also been developed by many investigators, for example a model considering log-normal size distribution have been created [27].

4.2 Modern models

Even though conventional models presented in previous chapter are still widely used in filtration calculations, also new models have been created more recently. The wide variety of different models created are based on different approaches, such as models based on conventional equations or models based on particle dynamics approach. Reviews of existing models have been made for example by Olivier et al. [40] and Lee et al. [41], which give further knowledge of wide variety of models existing. In this chapter, one different filtration model and one different approach assessing slurry filterability are introduced, to show examples of different approaches in filtration calculations.

4.2.1 Equivalent cake filtration theory

Equivalent cake filtration theory [42], created in 2008 by Xu et al., describes filtration for Newtonian and non-Newtonian fluids in different filtration stages. It can be used to predict filtration quality, if solid/liquid system properties and operation parameters are known, and to calculate specific cake resistance at various cake thicknesses.

In actual cake filtration, the liquid flows through channels which are difficult to describe mathematically. Equivalent cake filtration theory describes cake filtration by assuming cake consisting capillary tubes, where the fluid is free to flow. The flow rate through the tubes is equal to the flow through actual filter cake. The model assumes filter cake consisting capillary tubes, which radii is decreasing as cake is formed. The calculations are based on non-Newtonian capillary flow, which can be calculated using Navier-Stokes equations. The assumptions of the theory are following:

- The cake consists N capillary tubes, and no clogging occurs.
- All capillaries are straight and cylindral, with the same radii.
- Capillar height is equal to cake height.
- Liquid flow rate is equal of actual flow through filter cake in a certain pressure.

The calculations are based on Navier-Stokes capillary flow equations, with steady, incompressible and laminar fluid flow. The resulted equation is

$$R(t) = \left[\frac{Q(t)}{A}\frac{3n+1}{n\epsilon(t)}\right]^{\frac{n}{n+1}}\left[\frac{2\mu_0 l(t)}{\Delta P}\right]^{\frac{n}{n+1}}, \tag{4.11}$$

where $R(t)$ is equivalent radii of capillary tubes, Q(t) flow rate through real cake, A filter area, n non-Newtonian index, ϵ porosity, μ_0 viscosity point when shear rate is -1, $l(t)$ cake thickness [m], ΔP pressure difference [MPa]. For calculating filtrate flow, equation can be written as

$$Q(t) = Nq(t) = \left[\frac{A\epsilon(t)n}{3n+1}\right]^{\frac{n}{n+1}}\left[\frac{2\mu_0 l(t)}{\Delta P}\right]^{\frac{n}{n+1}}, \tag{4.12}$$

where N is the amount of capillary tubes in the cake. Specific cake resistance can be calculated from equivalent radii as

$$\alpha = \left(\frac{3n+1}{n\epsilon}\right)^n \frac{2}{R^{n+1}c}, \tag{4.13}$$

where c is dry solids mass per unit filtrate mass. In case of Newtonian fluid, when n=1 and $\mu = \mu_0$ the equation can be rearranged to

$$\alpha = \frac{8}{\epsilon(t)R(t)c}. \tag{4.14}$$

Using Eq. 4.11 and Eq. 4.13 equivalent radii $R(t)$ and cake resistance α can be calculated.

The Equivalent cake filtration theory gives new approach to calculate filtration parameters, such as cake resistance, but does not give any advice in predicting filterability from slurry collective characteristics. Therefore, also it's usage in this work is limited. In the flow calculations either equivalent radii of filtrate flux should be calculated prior to calculating the cake resistance, and slurry filterability are calculated from the filtration data. Also porosity is included to the calculations, which should as well be determined by experiments.

4.2.2 Approach in assessing slurry filterability

Even though calculating cake specific resistance from filtration data is widely used and accepted method to describe filtration properties, it has also received criticism for underestimating the complexity of the filtration phenomenon. Yukseler et al. [43] suggested, that the cake specific resistance should be related to the filter pore size which in practice affects filtration rate significantly. Also the operational conditions affect to the value of the specific cake resistance, and neither this is considered in the fundamental equations. Yukseler et al. also proposed a new method, which highlights the importance of particle and pore size interactions. The method is based on Hermia's approach [5], presented in Chapter 2.1, of blocking filtration laws. It is not an actual filtration model, since it presents only a slurry-specific parameter describing filterability better that the widely used specific cake resistance.

In the experimental part, two different slurry samples were filtered using Buchner funnel. With the first slurry, the effect of slurry concentration was investigated, and with the second slurry, the effect of pore-particle size interactions was investigated. With both experiments, in this new approach, the filterability can be expressed using K_{FC} [s^{-1}], which is a slurry specific parameter when only cake filtration, and no cloth blocking, occurs. While conventional method is based on calculation of the two resistance from t/V per V plot, in Yukseler's method the plot is calculated as $\mathrm{d}^2\mathrm{t}/\mathrm{dV}^2$ per dt/dV plot.

In Yukseler's work, the aim was to show the failure of using SCR for slurry characterization, and therefore synthetic slurries were used in the tests. Real sludge systems are more complex, and are more difficult to analyze through several different filtration mechanisms. Further work is needed to validate the method with real sludge systems. Therefore, the criticism to the widely used specific cake resistance is shown, but the work do not give an alternative for the specific cake resistance, which is suitable for real-life situations.

5. EXPERIMENTAL TESTS

Test series was committed to gather data for modeling part. The aim of the experimental part was twofold. Firstly, the difference in filterability with different slurries was investigated by comparing the filtration time with an ideal filter cloth at room temperature with 2 bar pressure. By using the same process conditions and the most suitable filter cloth for each slurry, the difference in filterability depends only at slurry properties. The properties that is known to have great effect on filterability were measured, and compared with each other. Secondly, the influence of process conditions was investigated by having a wider test series with three samples. The aim of the measurements were basically to compare the filtration rates, but also the cake and filtrate properties, such as cake dryness and texture, and filtrate purity, were measured.

5.1 Test procedure

The test series was committed using total 8 different slurries. Used slurries are two peat-based slurries (marked as Peat 1 and Peat 2), three lignin slurries (Lignin 1, 2 and 3) and three sedimented pulp mill sludges (Fibre 1, 2 and 3). Peat 1 and 2 are examples of easily filterable slurries. Lignin 1 and 2 were collected from Finnish pulp mill approximately one month before the test series started. Lignin 3 is known to be difficult-to filter slurry, and it was used as reference for the filterable slurries. Fibre samples are sedimented pulp mill sludge. The samples had thermal processing for different durations, which affected to the sample properties.

As the aim of this thesis was to find a way to predict slurry filterability from collective characteristics, a test series investigating slurry properties was committed. The properties investigated were chosen based on the theory of properties that are known to have a great effect on filterability. These properties are particle size distribution, particle shape, solid density, liquid density, liquid viscosity, pH, zeta-potential and conductivity, as described in Chapter 3.1. For particle size analysis, image analysis method IMG Fracon was used for big particles and dynamic light scattering (DLS) method Marlvern Mastersizer for small particles. Solids concentration and pH was measured with basic laboratory equipment, and rest of the properties were gathered from literature. The properties together with the analyzing method are presented in Table 5.1.

Table 5.1 *Analyzes for slurries*

Slurry properties	**Measurement method**
Particle density Liquid density Liquid viscosity	Internal data/Gathered from literature
Solids consentration Slurry pH	Laboratory measurements
PSD for particles > 1 μm Particle shape	IMG Fracon
PSD for particles 0.01 - 3500 μm	Malvern Mastersizer
Zeta-potential Conductivity	Malvern Nanosizer

Particle density, liquid density and liquid viscosity were determined mainly from internal knowledge of given slurry, but also literature reviews were used. Few assumptions were made considering mostly liquid density, which was assumed to be water for every slurry except Lignin 1 and 2. Solid consentration and slurry pH was measured in laboratory. Solids concentration was measured by heating a sample in a 105 °C oven overnight, and weighing the sample before and after. The pH was measured by using pH indicator paper.

The first method for analyzing particle properties was an image analysis method IMG Fracon, where particles in a diluted solution are pumped through a pipe. At one point the particle flow is photographed, and the particle properties are measured from the pictures. This method is suitable only for particles above 1 μm, because of the limits with camera resolution. The camera takes pictures of the flowing particles, and a software analyzes the pictures by finding the particles form the liquid, measuring the particle size, and therefore creating a size distribution. The size distributions can be created based on number, area or volume. Different particles can be sorted based on the shape or the size, and therefore dividing different particles to own groups is also possible. This equipment is designed mainly for analyzing fibers, particles and dirts, so the method was well suitable for slurries investigated in this thesis.

Another particle size analyze was made by Malvern Mastersize, which uses dynamic light scattering (DLS). Mastersize gives the whole needed size range from 0.01 - 3500 μm, but assumes spherical particles, so the particle shape can not be included to the size distribution. Malvern Nanosizer was used to measure zeta-potential and conductivity. Nanosizer is a measurement tool for colloidal particles, and the upper limit for particles suitable for the measurement is 5 μm. Because of the limitation of particle sizes, and the fact that the most of the slurries include bigger particles than 5 μm, the zeta-potential and conductivity were measured from the filtrate. This includes the assumption, that the zeta-potential and conductivity values are equal in the filtrate and in the slurry before filtration.

The test were done based on a matrix presented in Fig. 5.1. The filterability of each slurry was tested in a 2 bar pressure at room temperature with the most suitable filter cloth. A wider test series was made with three slurries, Peat 1, Lignin 1 and Lignin 2, consisting different temperature and pressure levels. Used pressure levels were 2, 4 and 6 bar, and temperature levels 20, 45 and 65 Celsius degrees. Also at least one point inside the matrix was tested with each slurry, to test the effect of sum of the forces.

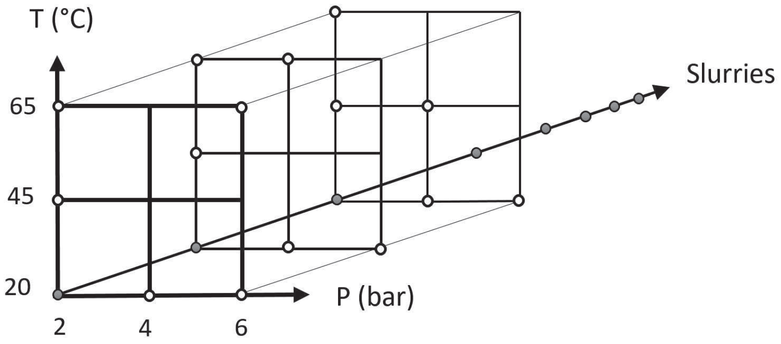


Figure 5.1 *Test matrix*

Also few individual tests outside the matrix were made. The rest tests are presented in Table 5.2. Effect of increasing pressure profile was tested with Peat 1, Lignin 1 and Lignin 2. The pressure increase was from 1 to 6 bar, and the manually done pressure increase was done as stable as possible. Effect of changing filter cloth was tested with Lignin 1 and 2, including 3 different filter cloths. Also effect of modified pH by adding NaOH was measured with Peat 1.

The other effects, such as test environment, was kept as stable as possible. The

Table 5.2 *Tests outside the matrix*

Test	Description	Used slurries
Increasing pressure profile	from 1 to 6 bar	Peat 1, Lignin 1 and Lignin 2
Difference in cloth seletion	3 different cloths	Lignin 1 and Lignin 2
Effect of modified pH	pH 4, pH 7 and pH 9	Peat 1

pressure was constant in all tests, excluding the tests where the effect of increasing pressure profile was investigated. The filtration was stopped when air-break through the cake occured, and the filtration time was measured. The pressing and air-drying duration is 60 seconds in all test. The applied pressure in the pressing and air-drying part is same as in the filtration part. All tests were made twice to confirm the result. The samples were stirred continuously before and between the tests to prevent particle settling and therefore changes in slurry concentration. With slurry conditioning, the sludge was heated to a few degrees higher temperature, to prevent sludge cooling too much during portioning. Amount of inserted slurry was 200 g with Peat 1, Lignin 1 and Lignin 2, and 100 g with the rest of the samples.

5.2 Filtration equipment and cloths

A dead-end filtration cell `FILTRATEST`, manufactured by Bokela, was used in the experiments. The filtration equipment was located in Valmet Fabrics laboratory in Tampere, and all the tests were done there. The equipment consists a cylinder made of stainless-steel, filtration area of 19,63 cm^2. Pressure range of the device is up to 10 bar, but was limited to 6 bar by the maximum pressure of compressed air in the mill line. The maximum amount of inserted slurry is 380 ml, and the filter cake thickness should not exceed 50 mm. The equipment can be used in filtration, compression, cake washing and deliquoring for both pressure and vacuum filtration. [44]

The scheme of equipment is presented in Figure 5.2. The gas flow measurement device is on the left side, and the pressure can be reduced by rotating the pressure valve, which can be seen in the middle of the figure. The actual filter cell is in the right side of the figure. The amount of received filtrate was measured using scale, and the whole device is connected to the computer, so the amount of received filtrate, air flow and pressure in the cell could be measured.

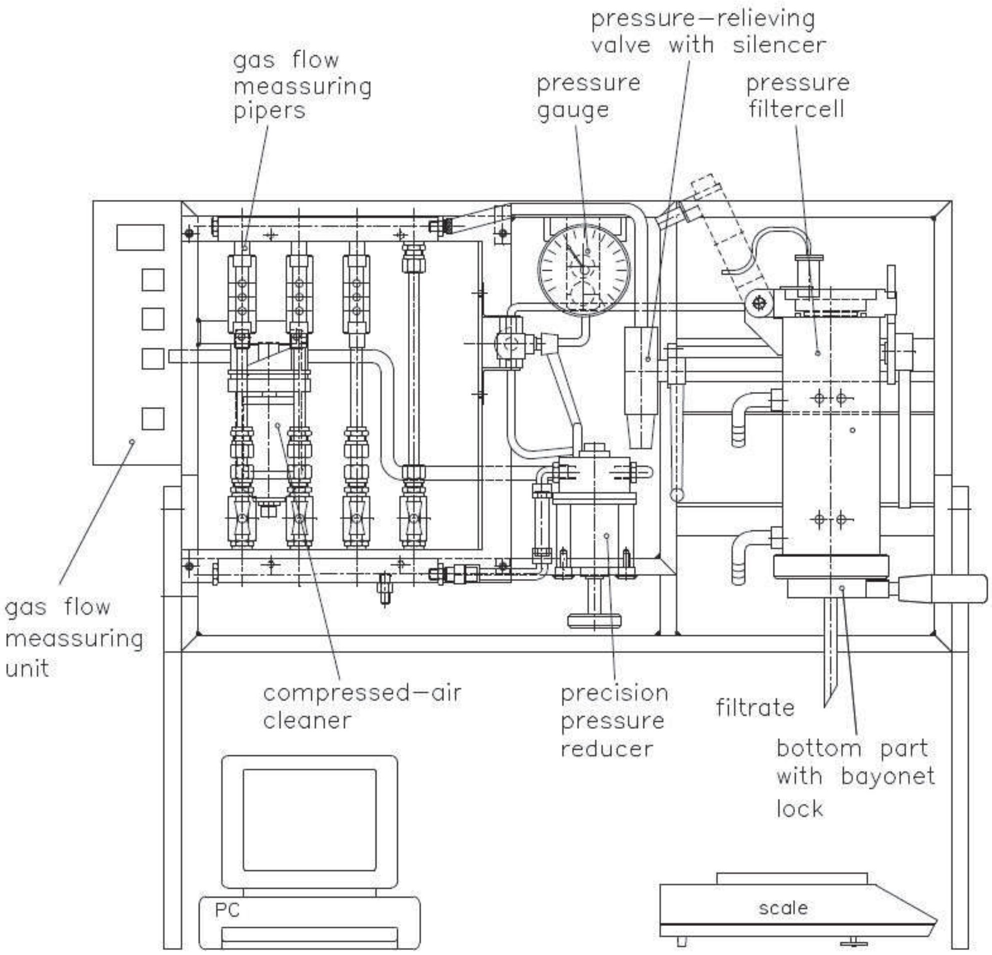


***Figure* 5.2** *Filtratest [45]*

Variety of different filter cloths were used, since the differences between used slurries cause the need of different filter cloth properties. The aim was to have the optimal filter cloth for each slurry, and cloth selection was committed with a filtration specialist. The selected filter cloths for the experiments were `S1117-S2K2`, `S1115-S2K2`, `S1112-S2K2` and `S1141-R1K2`. All of the used cloths are Valmet Fabrics products. Some of the cloth properties are presented in Table 5.3. Table shows weave type, yarn type which is either mono- or multifilament, media weight in g/m^2, air permeability at 200 Pa expressed in m^3/m^2 min, and cloth thickness in mm.

First three cloths were mainly used for slurries with small particles, which includes Peat 1 and lignin samples. The cloths `S1141-R1K2` was used for the fibre samples and Peat 2, which include bigger particles.

Table 5.3 *Filter cloth properties*

Media	**Weave**	**Yarn**	**Weight** [g/m^2]	**Air permeability** [m^3/m^2 min]	**Thickness** [mm]
`S1117-L2K2`	7/1 Satin	Monofilament	550	10.0	0.8
`S1115-L2K2`	14/2 Satin	Monofilament	490	5.0	0.9
`S1112-L2K2`	14/2 Satin	Monofilament	455	1.0	0.6
`S1141-R1K3`	2/2 Twill	Monofilament	270	78	0.6

5.3 Results

5.3.1 Slurry properties

Basic slurry properties used in the modeling were solid density, liquid density, liquid viscosity and slurry pH. These values for each slurry are presented in Table 5.4. All values are measured at 20 °C temperature. Values, mainly liquid viscosity and density, are also depending on temperature, and therefore also values for 45 and 65 °C were measured. They are presented later in Chapter 6.3.

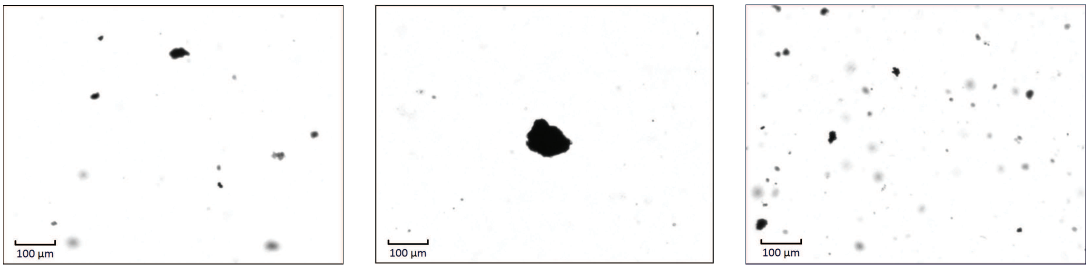
Table 5.4 *Slurry properties*

Slurry	**Solids consentration [%]**	**Solids density [kg/m3]**	**Liquid density [kg/m3]**	**Liquid viscosity [Pa s]**	**pH**
Peat 1	10.7	1350	1000	0.001	3.8
Peat 2	10	1120	1000	0.001	7
Lignin 1	36.5	1220	1225	0.02	10.9
Lignin 2	25	1220	1135	0.004	2.4
Lignin 3	5.2	1100	1000	0.001	8.5
Fibre 1	11.10	1100	1000	0.001	4
Fibre 2	9.39	1100	1000	0.001	3
Fibre 3	8.55	1100	1000	0.001	3

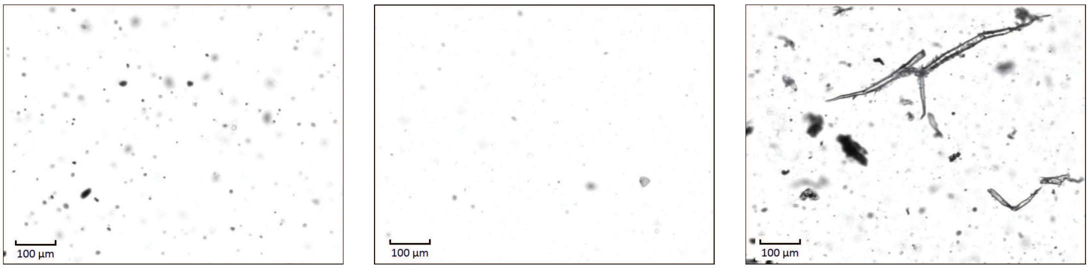
With both lignin samples, data considering all properties presented was available. For the rest of the samples measurements and some assumptions were made. Solids concentration and pH were measured experimentally for the rest samples. With solids density, liquid density and liquid viscosity the exact values could not been measured. The liquid phase for all samples excluding lignin samples was assumed to be pure water, so as liquid density and viscosity, water properties were used.

Also solids density with fibre samples was evaluated based on previous knowledge of samples alike these materials, so these values are only estimates of the real values.

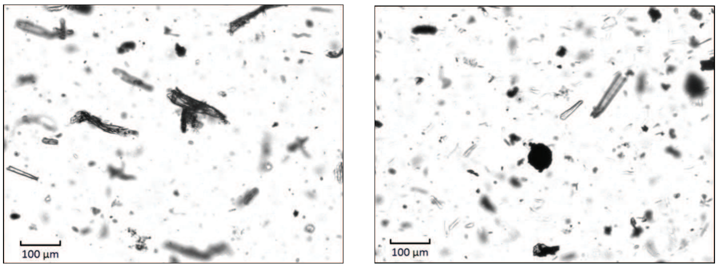
As image analysis method IMG Fracon was used to describe the size distribution, images of each sample can be represented, and the particle shapes for each sample can be analyzed. The scale is same in all figures, so also the particle sizes are comparative. The figures of each sample is represented in Figure 5.3.



(a) Peat 1 (b) Peat 2 (c) Lignin 1



(d) Lignin 2 (e) Lignin 3 (f) Fibre 1



(g) Fibre 2 (h) Fibre 3

Figure 5.3 *Sample figures*

Figure 5.3 shows that the samples are quite different with each other by size and shape. Peat and Lignin samples have spherical-shaped particles, while Fibre samples have big, fibrous particles, together with small spherical particles. Also Peat 2 have some really big-sized particles, compared to Peat 1. Lignin 1 and 2 seem quite similar with each other, even though Lignin 2 has slightly smaller particles compared to Lignin 1. Image of Lignin 3 is also interesting, since the concentration is much smaller compared to the other lignin samples, even though the amount of inserted slurry was similar. This indicates that majority of the particles are below 1 μm, and IMG Fracon cannot see the particles.

The particle size distribution measurement for all samples were made firstly by using IMG Fracon, but also by Malvern Mastersizer, to find out if the slurry includes particles < 1 μm, which IMG Fracon cannot see. The resulted size distributions are presented separately for small-sized particles and bigger sized particles. Small-sized particles are Peat 1, Lignin 1 and Lignin 2 and bigger-sized particles Peat 2 and all fibre samples. The PSD of Lignin 3 is presented separately.

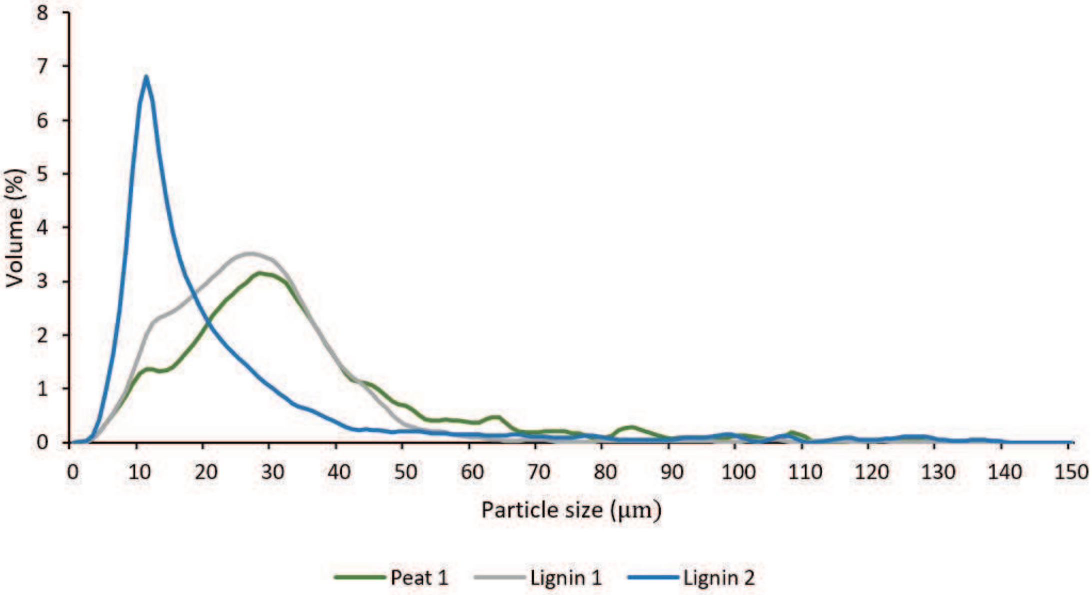


Figure *5.4 Particle size distribution for small-sized samples*

The particle size distributions for all samples are presented in Figures 5.4, 5.5 and 5.6, and are divided based on the particle size measurement results. In Fig. 5.4 are the PSD:s for Peat 1, Lignin 1 and Lignin 2, which have average particle size below 30 μm. In Fig. 5.4 the PSD are presented for bigger-sized particles, which include Peat 2 and all fibre samples. In Fig. 5.6 are Lignin 3, which was the only sample having majority of particles below 1 μm. The size distribution were measured twice, firstly by using IMG Fracon. Another measurement was done by using Malvern Mastersizer to find out if particles below 1 μm exist. The results of the measurements were, that only with Lignin 3 the particles below μm have an important role. Therefore the

PSD with Lignin 3 is based on the Malvern measurements, while the others are based on IMG Fracon measurements.

The particle size distributions for small-sized samples are presented in Figure 5.4. Lignin 2 has clearly the most mono-sized distribution of these samples, having just one clear peak. Peat 1 and Lignin 1 have somehow similar size distribution, as there is a top around 28 μm, but also another small increase in particles at 12 μm.

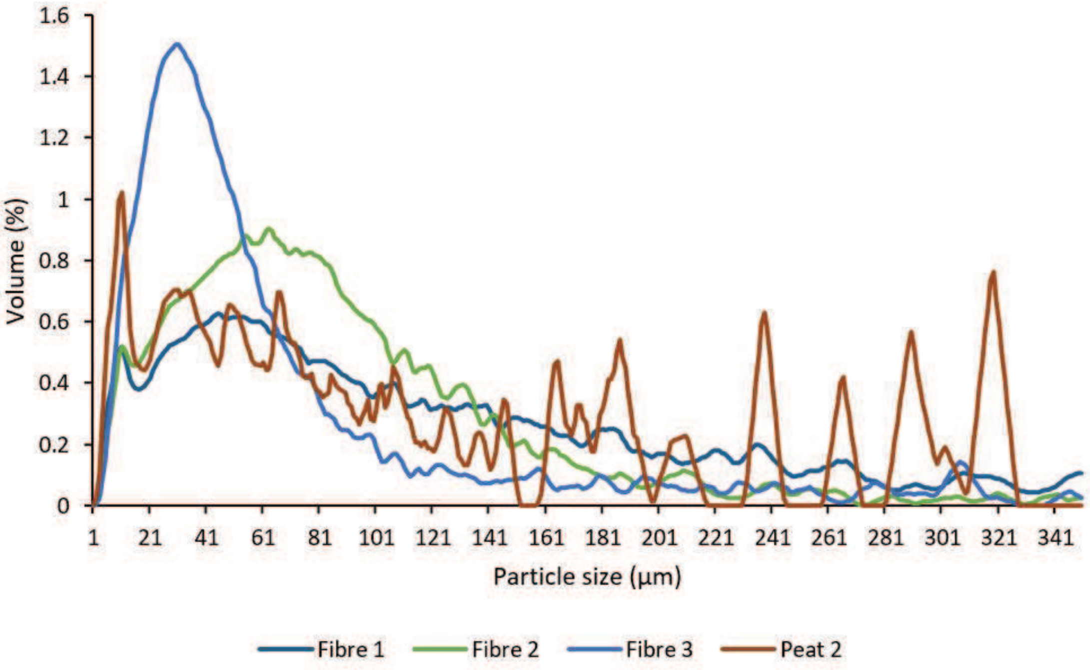


Figure 5.5 *Particle size distribution for bigger-sized samples*

PSD for bigger-sized particles, including fibre samples and Peat 2, is represented in Figure 5.5. The mean particle size is slightly higher, being above 40 μm for all samples. The size distribution is also clearly wider compared to the previous PSDs, since the peak is below 2 vol-%. Fibre 3 shows quite monosized PSD compared to the other samples in the graph. If the distribution width is compared to lignin samples or Peat 1, all samples in this graph have much wider size distribution. Peat 2 has some individual big particles, which have significant effect to the volume-based PSD, and make the size distribution look rough.

Lignin 3 has it's own PSD, since it was the only sample, which had majority of particles < 1 μm. Malvern Mastersize measurements showed, that the other samples do not have particles below 1 μm, expect Lignin 3. Therefore, the PSD of Lignin 3

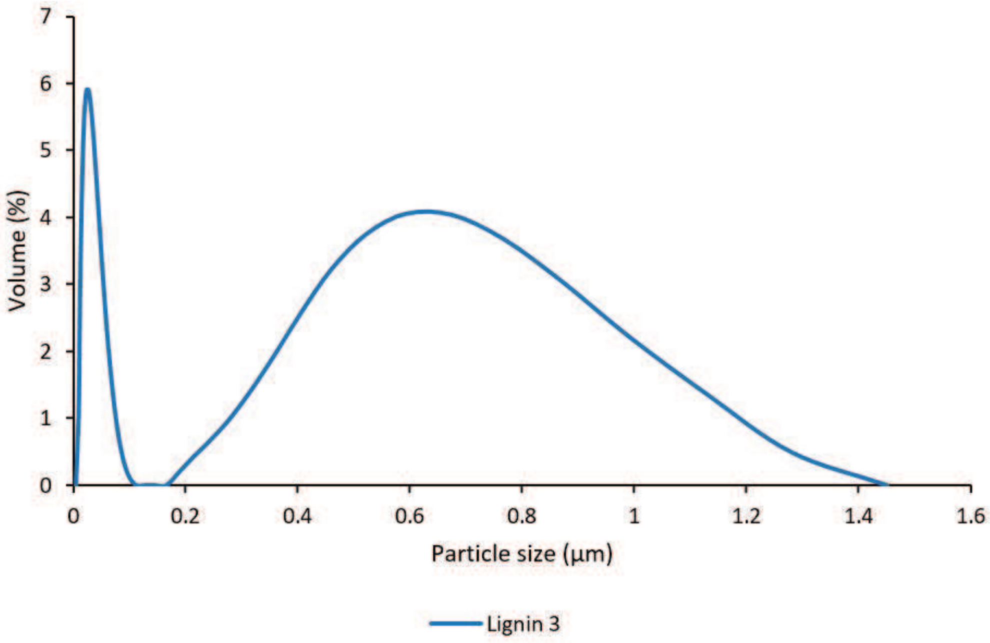


Figure 5.6 *Particle size distribution Lignin 3*

is introduced separately. Lignin 3 has two separate peaks, at 0.6 μm and 0.03 μm. Between the peaks, there are no particles in between 0.1 and 0.2 μm. The greatest peak is at 0.003 μm, where is almost 6 volume-% of particles, but also in the second peat at 0.6 μm is 4 volume-%.

5.3.2 Filtration results

In this chapter, the filtration results are introduced. Firstly, an example of the full filtration cycle is presented, and the amount of received filtrate for each sample is compared with each other. The filtration curves for all samples are compared, and the effect of increasing pressure and temperature on cake formation time and cake dryness are shown for Peat 1, Lignin 1 and Lignin 2. The cloth selection is compared with Lignin 1, and the effect of changes in pH in cake formation time and cake dryness are represent for Peat 1. In the end of the chapter, the filtration curves for slow pressure increase and constant-pressure filtration are compared.

From every experiment, `FILTRATEST`-program saved the filtration curves for filtration, pressing and air-drying steps. The whole filtration cycle with all these steps are presented in Figure 5.7 for Peat slurry 1. In the figure filtration, pressing and air drying steps were all committed in 2 bar pressure and 20 °C temperature. The filtration time was stopped manually when the filtration was ready. With pressing and air-drying the duration was settled to 60 seconds. The amount of filtrate received in each filtration step is one subject of interest. With the presented Peat slurry 1, the majority of filtrate is gathered in the filtration part. The amount of filtrate is increasing only a slightly at pressing and air-drying part, so in this case those steps do not have an enormous effect to the filtration efficiency.

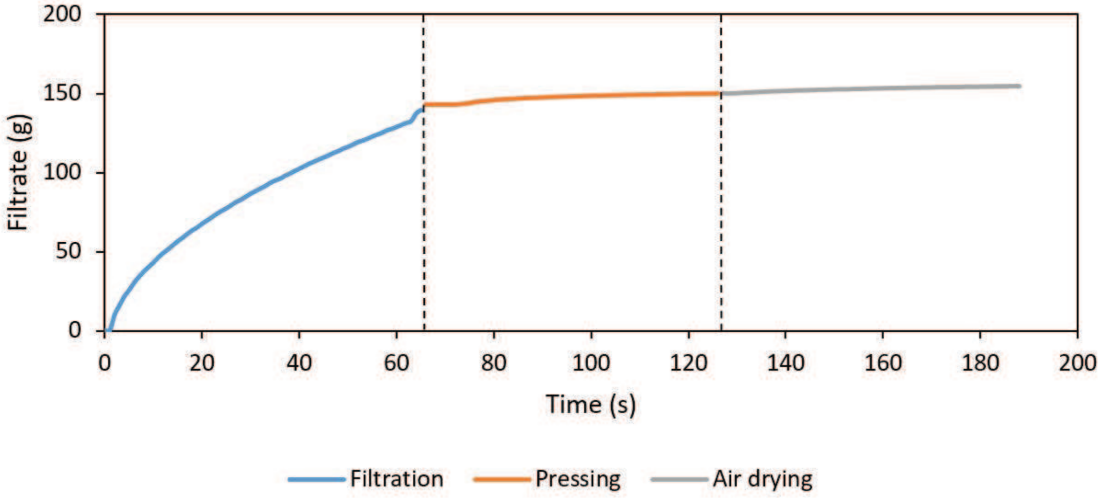


Figure 5.7 *Filter cycle for Peat 1*

For the other samples, the gathered filtrate in every part of the filtration cycle is varying more. The amount of received filtrate is represented in Figure 5.8. The greatest amount of filtrate is received in filtration part with every substance, being more that 70 % of filtrate received in filtration step with all substances, but even more with majority of the samples. The first three slurries, Peat 1, Lignin 1 and Lignin 2 have quite a small difference in the pressing and air drying parts. In percentages, the last two steps gather less than 9 % of the total filtrate, while with Fibre 1, Fibre 2, Fibre 3 and Peat 2 the pressing and air-drying parts produce more than 9 %. The greatest effect is with Fibre 1, where the last two steps produce as much as 24.2 % of the filtrate.

It should be noted, that in Fig. 5.8 the pressing and air-drying steps are not optimized. All steps were done in room temperature with 2 bar pressure, with 60 seconds of pressing and air-drying donation. Using different pressure levels and donations naturally affects to the amount of received filtrate. Also the graph is presented

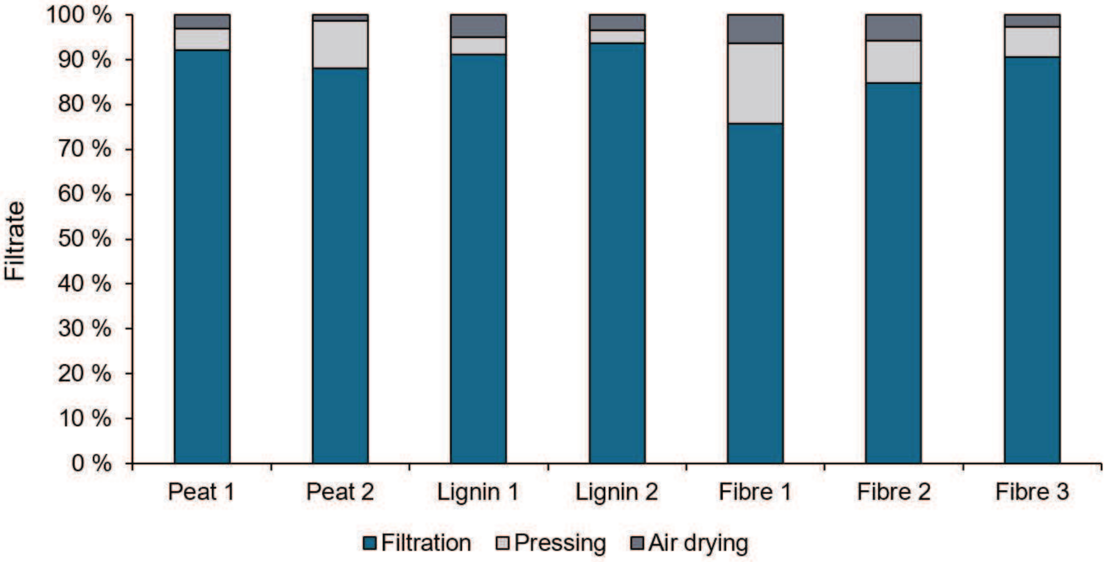


Figure 5.8 *Received filtrate with every step*

in percentages of filtrate, and the amount of received filtrate in grams varies quite much with the samples.

Even though the pressing and air-drying steps in the filtration cycle do have a great role with filtration efficiency, the most important part of the process is the filtration step, where majority of the filtrate is received and which affects the most to the rate of the whole cycle. These filtration rates are presented in Fig. 5.9 for each slurry. From the figure can be seen, that while the filtration time varies quite much, also the received filtrate is varying with used slurries. The huge differences of received filtrate have at least two main reasons. Firstly, the amount of inserted slurry differs with the samples. The lignin samples with Peat 1 had inserted slurry amount of 200 g, while the fibres and Peat 2 had the amount of 100 g, which naturally have a great effect to the amount of achieved filtrate. Secondly, the slurry concentration is not same with all slurries, and that have also effect to the amount of filtrate received. Beside these reasons, also other factors, such as cake properties, affect to the received filtrate, but these properties are more complicated, and have less impact than for example the amount of inserted slurry.

The Figure 5.9 also shows clearly the differences in filtration rate with the slurries. Even though fibres 1 and 2 have smaller cake formation time compared to Peat 1, the reason is not because of higher filtration rate, but because of lower amount of

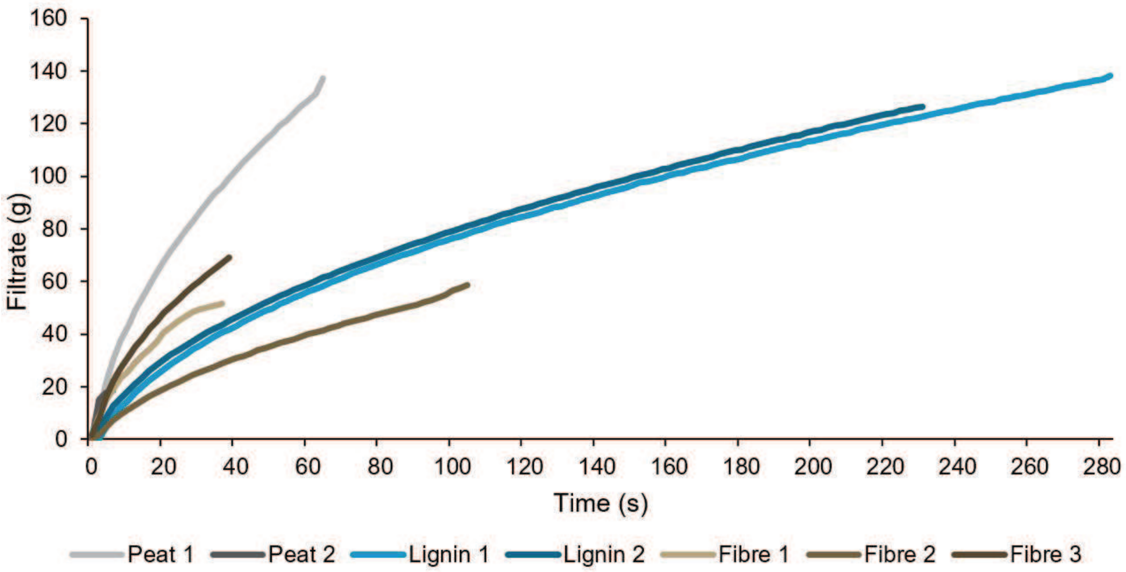


Figure 5.9 *Filtration curves for each sample*

inserted slurry and therefore also lower amount of gathered filtrate.

With different process conditions, the cake formation time followed the conventional filtration theory, which was presented in Chapter 4.1.2. In Figure 5.10 is the cake formation time expressed as a function of pressure in constant temperature, and as a function of temperature in a constant pressure. Increasing values of both pressure and temperature caused the cake formation time to decrease. The influence of pressure is approximately linear, but with the increasing temperature, the step from 45 to 65 degrees causes greater impact on filtration rate than the temperature change from 20 to 45 degrees especially with Lignin 1. From the graph the differences between different sludges can also be seen. The Lignin 2 gives the slowest filtration rate, while the Peat slurry 1 gives the most rapid filtration rate. The great differences between the two measurements between Lignin 2 are because in the first measurement, the inserted amount of slurry was 150 g.

As well, the cake dryness was calculated and is expressed in the same way, as a function of temperature and pressure. The dryness in presented in Figure 5.11. Also cake dryness increases with increasing temperature and pressure. The relationship between cake dryness and increasing pressure is not linear with the samples, since a small curve in the slope can be seen. The effect of increasing temperature looks linear for Peat sample 1, but with lignin samples, the temperature change from 45

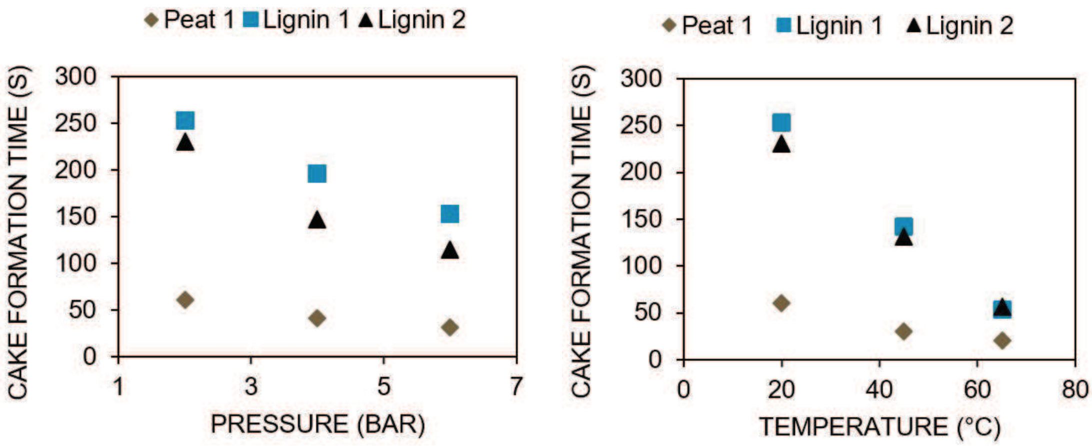


Figure 5.10 *Cake formation time as function of pressure and temperature*

to 65 degrees show the greatest effect.

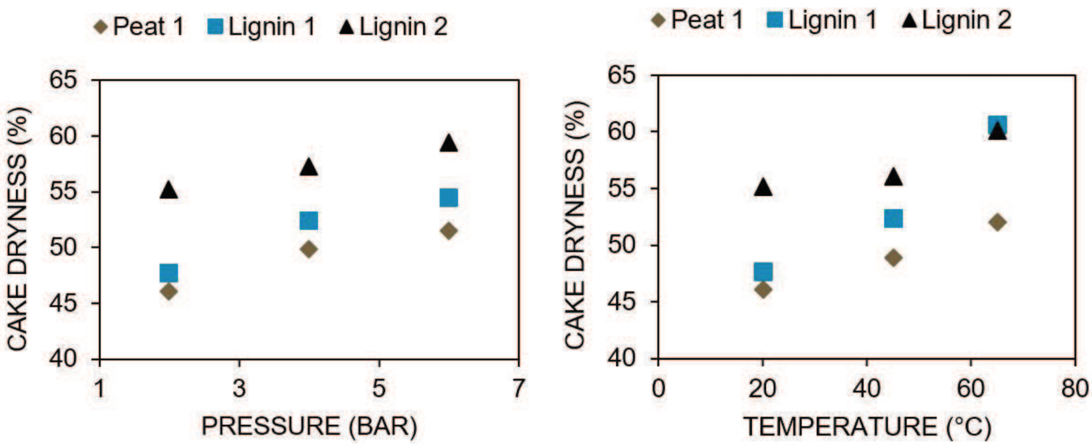


Figure 5.11 *Cake dryness as a function of pressure and temperature*

Differences in cloth selection were investigated with Lignin 1 by testing three different filter cloths: `S1117-S2K2`, `S1115-S2K2` and `S1112-S2K2`. As Fig. 5.12 shows, the used cloths gave slightly different cake formation time, but the differences were not enormous. Cloth `S1112-S2K2` gave slowest filtration rate, while `S1117-S2K2` gave the most rapid rate, but the difference with the first tests were only few seconds. Moreover, the effect of media blinding can be seen from the figures. In every test, the first round with a clean media gave better efficiency than the second round with used media, even though the filter cloth was cleaned between the experiments. Despite the cleaning, some particles most likely got caught to the filter media pores and therefore slowed the filtartion rate in the second experiment

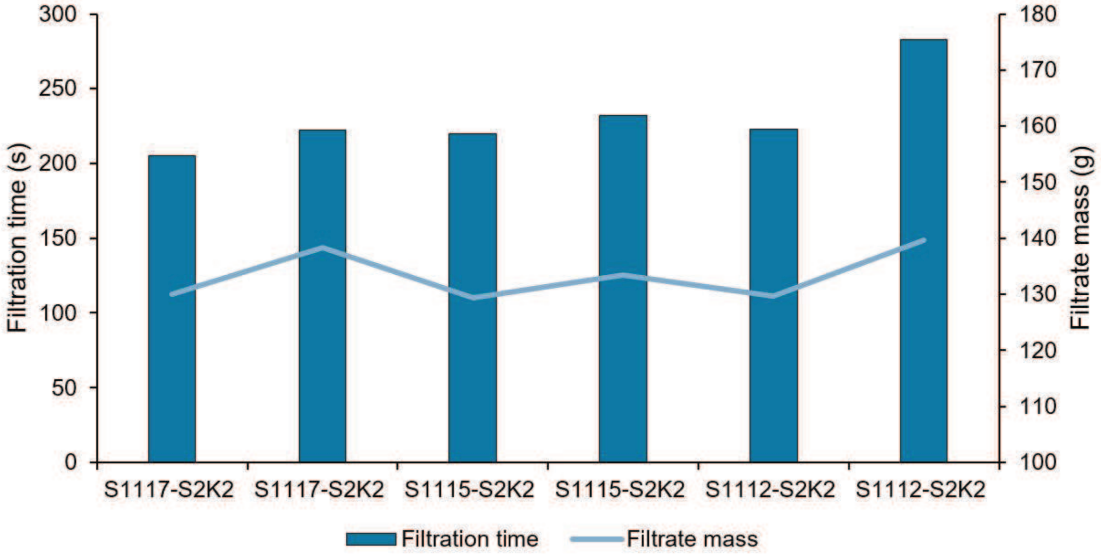


***Figure* 5.12** *Different filter cloths with Lignin 1*

Differences in changing pH was investigated with Peat slurry 1, which has original pH around 4. Sodium hydroxide NaOH was added to the two different slurry batches, so that the first one achieved neutral pH 7, and the second sample achieved alkaline pH 9. Filtration tests with 2 bar pressure and room temperature were committed to these slurries. In all tests the filter cloth were `S1117-S2K2`. The pH value was measured with pH indicator paper, so the values of pH are not fully accurate.

The test series were committed twice. In the first test round, the filtrate created foam with both samples with increased pH. This was assumed to have an effect to the results, so the test series was repeated. Also the batch was stirred for only a short time, approximately 1 minute, with quick stirring rate, and the effect quick stirring was unclear. Because of the uncertainty of these aspects, the results were verified with another test series. With the second test, the slurry was stirred for longer time, approximately 10 minutes continuously, with slower rate. With longer stirring duration, the added NaOH could react properly, and foaming during filtration did not occur. The filtration times from both measurements are represented in Figure 5.13.

The second test series confirmed, that the foaming and the short time period of quick stirring in the first test series did not have a great effect on the filtration rate. The changes in slurry pH have remarkable effect on cake formation time in both measurements - the slurry with neutral pH has two times longer cake formation time compared to the slurries with acidic or alkaline pH. The reason behind this behavior is unclear, and the result do not agree with the theory of isoelectric point represented in Ch. 3.3.2.

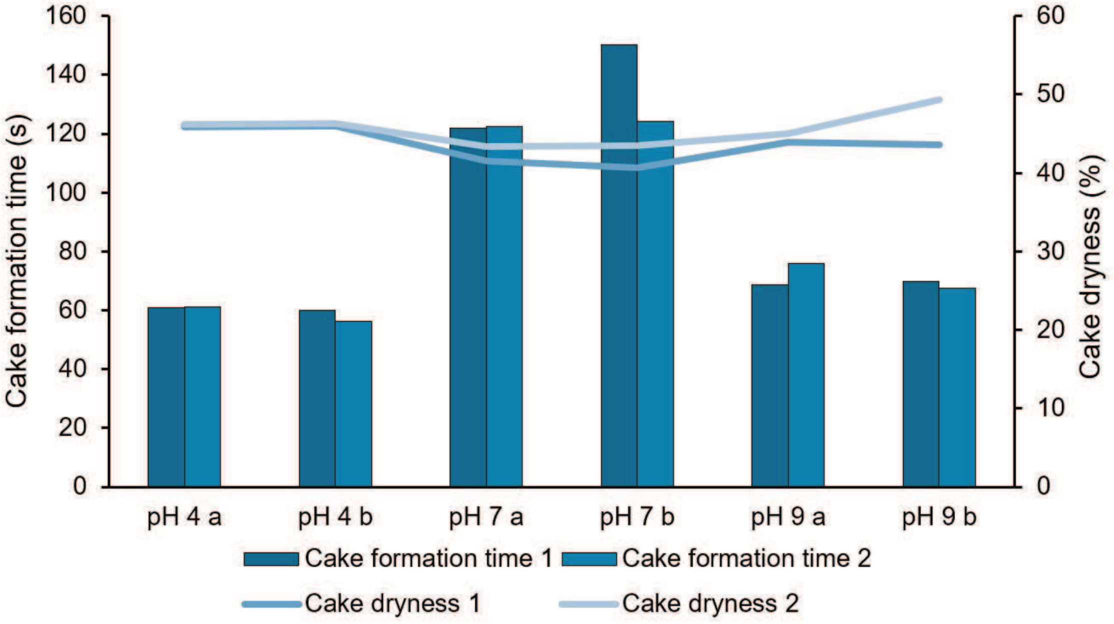


Figure 5.13 *Effect of pH in the filtration time and the cake dryness with Peat 1*

Beside differences in filtrate flow, also cake dryness depends on pH in these tests, not as much as cake formation time but still remarkably. The highest cake dryness is achieved with the original slurry, having approximate pH 4. With this cake, the dryness of 46 %, respectively. The greatest moisture content occured with pH 7, which also haves the slowest cake formation time.

Effect on slow pressure increase was investigated with three different slurries, Peat slurry 1, Lignin slurry 1 and Lignin slurry 2. The pressure increase was meant to be as constant as possible, but since the pressure was increased manually, the increase rate is not constant. Neither the rate is identical with the other measurements. With all samples, increasing pressure profile slowed down the filtration time. In Figure 5.14 the effect of slow pressure increase with constant pressures of 2 and 6 bar is represent for Lignin 1.

With Lignin 1, the increasing pressure profile caused the filtration curve to be slightly more linear compared to constant-pressure filtration. In the beginning of filtration, the flow rate is remarkably lower compared to both, constant-6-bar and constant-2-bar filtration. After approximately 50 seconds of filtration, the pressure has been probably increased near 6 bar pressure, since the rest of the filtration curve follows the 6-bar curve.

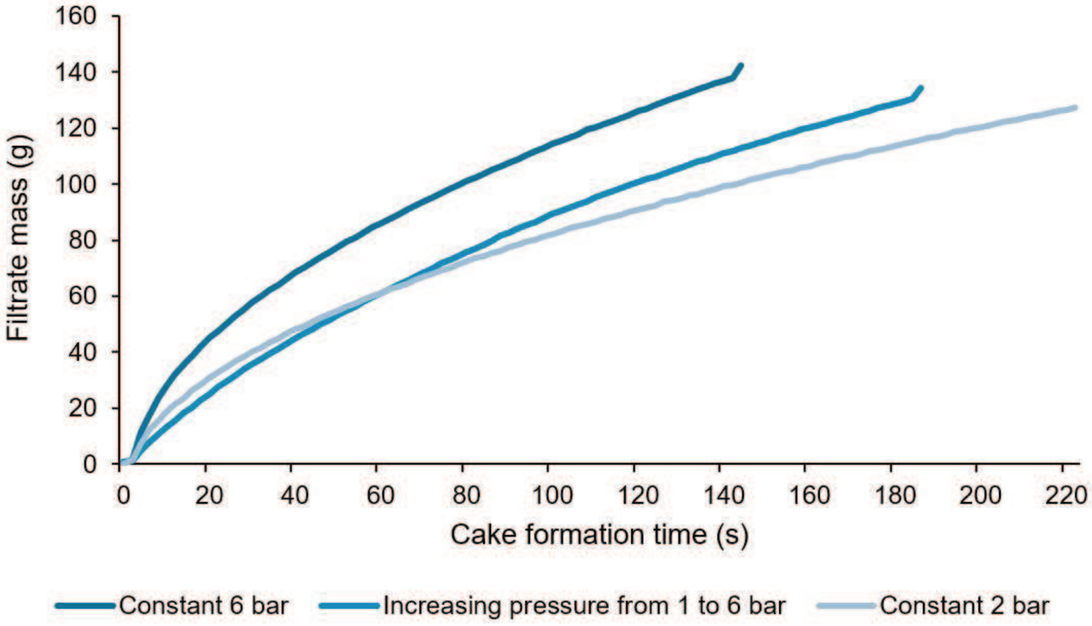


Figure 5.14 *Effect of increasing pressure profile with Lignin 1*

Notable is also that beside the cake formation time, also the amount of filtrate is different with the experiments. 6 bar pressure gives highest amount of filtrate, while 2 bar pressure gives the lowest amount of filtrate. As the amount of inserted slurry is similar with each sample, the received filtrate refers that with 6 bar pressure the cake is drier than with increasing pressure levels of with 2 bar pressure.

6. MATHEMATICAL MODELING

As the main purpose of this thesis was to create a way to predict slurry filterability, the variables presented earlier are fitted to a mathematical model. In this section three different models are represented. First model is straightly based on conventional mathematical equations, calculating cake specific resistance from Kozeny-Carman equation, which is the only wide-known method for estimating cake specific resistance. The second model of estimating cake specific resistance is lumped model, which is not based on any equation presented earlier. It was created by finding correlations between measured data, mainly from particle size distribution properties and filtration results. Third model is a linear regression model, where correlations were calculated by using regressions between variables, and therefore creating a straight slope. The effect of process variables was calculated by using the conventional cake filtration theory, and the calculated valued were compared to the measured values.

6.1 Introduction to the modeling tools

The created models were designed to follow the classical filtration theory, where the models try to predict cake specific resistance for each slurry. As the specific cake resistance was in interest, variables such as filter area, liquid viscosity and slurry concentration could be dismissed from the calculations. This simplifies the modeling part by reducing the number of variables. The specific cake resistance was firstly calculated for the used slurries, and the modeling part was committed based on these calculated resistance values.

The specific cake resistance was calculated for each slurry from filtration data, when the most suitable filter cloth and 2 bar pressure in the room temperature was used. The calculation method for cake and media resistance was made using conventional cake filtration theory, introduced previously in Ch. 4.1.2, by plotting filtration time divided by filtrate volume (t/V) per filtrate volume (V). Then the cake resistance was calculated from the slope and the media resistance from the intercept. The resulted slopes from the data, and the calculated slope parameters can be found from Appendix B.

Also `FILTRATEST` calculated the resistances for each slurry. In Table 6.1 are both resistance values for the cake, calculated from the slope and measured by `FILTRATEST`. The two values presented are quite similar. Some inaccuracy occurs especially with Peat 2, and the reasons behind the great difference are explained further.

Table 6.1 *Calculated and measured cake resistance*

Slurry	**Test no.**	R_c calculated $[1/m^2]$	R_c measured $[1/m^2]$
Peat 1	545	4.30E+12	3.74E+12
Peat 2	523	3.10E+11	7.63E+12
Lignin 1	557	9.22E+11	7.02E+11
Lignin 2	597	4.6E+12	8.46E+12
Lignin 3	–	–	–
Fibre 1	610	1.2E+13	1.35E+13
Fibre 2	587	3.2E+13	3.28E+13
Fibre 3	608	9.2E+12	8.84E+12

Similarly, the media resistance was calculated from the slope and measured by `FILTRATEST`. In Table 6.2 are the resistance values for the media. In modeling the values calculated from the slopes are used.

Table 6.2 *Calculated and measured media resistance*

Slurry	**Test no.**	R_m calculated $[1/m]$	R_m measured $[1/m]$
Peat 1	545	4.38E+10	5.5E+10
Peat 2	523	1.0E+9	–
Lignin 1	557	8.8E+9	2.3E+10
Lignin 2	597	3.1E+10	5.5E+10
Lignin 3	–	–	–
Fibre 1	610	4.6E+10	5.8E+10
Fibre 2	587	2.4E+11	2.6E+11
Fibre 3	608	5.54E+10	5.60E+10

The slopes could not be calculated for two slurries, Peat slurry 2 and Lignin 3. With Peat 2, the calculation could not be committed properly, since the air-blown through the cake was immediate. The total filtration time was marked to be 8 seconds in the test results, but the actual air-blow happened much quicker. The graph from the whole filtration time of 8 seconds gave negative values for the media resistance, which can't be true. Because of that, only the first 3 seconds of filtration was taken into account on the calculations. This causes the resulted values to be inaccurate, since forming a slope with just three points do not give exact results. Hence, since filtration was extremely quick, the cake resistance is known to be relatively low, and the value calculated from the first three seconds of filtration gives an adequate estimate of the cake resistance for the purposes of this work. Also resistance value with Lignin 3 was just estimated, since filtration data with Lignin 3 do not exist. Filtration was stopped after a few minutes since the filtration was started, due to very slow filtration rate.

Table 6.3 shows the resistance values in form m/kg, which are used in the modeling. Cake specific resistance α was calculated from the cake resistance R_c by dividing it by dry cake per filtrate volume [kg/m^3]. Since the filtration curves for Lignin 3 do not exist, the value presented in Tab. 6.3 are estimates of very high filtration resistances. The calculated media resistances do not show any correlation with each other even though the same media was used. Instead, the media resistance seems to depend on the cake resistance. The value of media resistance is with all samples around two magnitudes smaller than cake resistance. The value of media resistance can not be ignored in the calculations, since it does have a great effect in overall filtration rate, but to simplify the calculations for modeling the medium resistance was assumed to be 0.0075 times the cake resistance.

Table 6.3 *Used resistance values in modeling*

Slurry	α $[m/kg]$	R_m $[1/m^2]$
Peat 1	3.57E+10	3.35E+10
Peat 2	1.26E+10	3.70E+10
Lignin 1	4.74E+09	6.88E+09
Lignin 2	1.76E+10	3.64E+10
Lignin 3	1.00E+14	7.50E+13
Fibre 1	8.08E+10	8.66E+10
Fibre 2	3.01E+11	2.38E+11
Fibre 3	1.09E+11	6.88E+10

Inputs for the calculations are specific cake resistance α, filtration area A, pressure difference ΔP, viscosity ρ, slurry concentration s, liquid density ρ and cake moisture ratio m. All the variables can be measured before the filtration, expect the cake moisture ratio, which have to be assumed. The moisture ratio was set to be 2 for dispersions with small particles and 3 for dispersions with coarse particles. The input values are shown in Table 6.4.

Table 6.4 *Data for calculating filtrate flux*

	Peat 1	**Peat 2**	**Lignin 1**	**Lignin 2**	**Fibre 1**	**Fibre 2**	**Fibre 3**
A [m^2]	0.00196	0.00196	0.00196	0.00196	0.00196	0.00196	0.00196
ΔP [Pa]	200000	200000	200000	200000	200000	200000	200000
μ [Pa*s]	0.001	0.001	0.02	0.004	0.001	0.001	0.001
s [w/w]	0.1	0.18	0.12	0.17	0.1	0.08	0.07
ρ [kg/m^3]	1000	1000	1225	1135	1000	1000	1000
m [-]	3	3	2	2	3	3	2

With the presented values, including the calculated specific cake resistance, the filtrate flux can be calculated. To see how the two assumptions used - assumption of calculating media resistance from cake resistance value, and assumption of moisture ratio being between 2 and 3 for all slurries - affect to the actual filtration rate, the measured filtrate flux and calculated filtrate flux are compared with each other. The comparison is presented in Figure 6.1.

Figure 6.1 shows that the measured and calculated values are almost identical with majority of the samples. Nevertheless, with Lignin 2, the calculated slope is slightly different from the measured value, offering slower cake formation time. The error with calculated and measured filtration time is around 10 seconds with Lignin 1. Also with Fibre 2 small inaccuracy can be seen. Fibre 3 has slightly slower filtration rate calculated compared to the measured values. Also with Peat 2 and Fibre 1, the slopes have small inaccuracy. Nevertheless, with the used samples the two assumption used give an adequate estimation of filterability compared to the measured values.

The other disagreement is the filtration time. The conventional cake filtration theory, which was using to calculate the filtration flux of the substances, does not comment on the filtration time - it assumes the filtration to continue to the infinity. With the calculated values shown, the filtration was stopped when the amount of filtrate reached the amount of actual amount of filtrate. It should be noted, that when predicting filterability, the actual amount of received filtrate can not be predicted with this model.

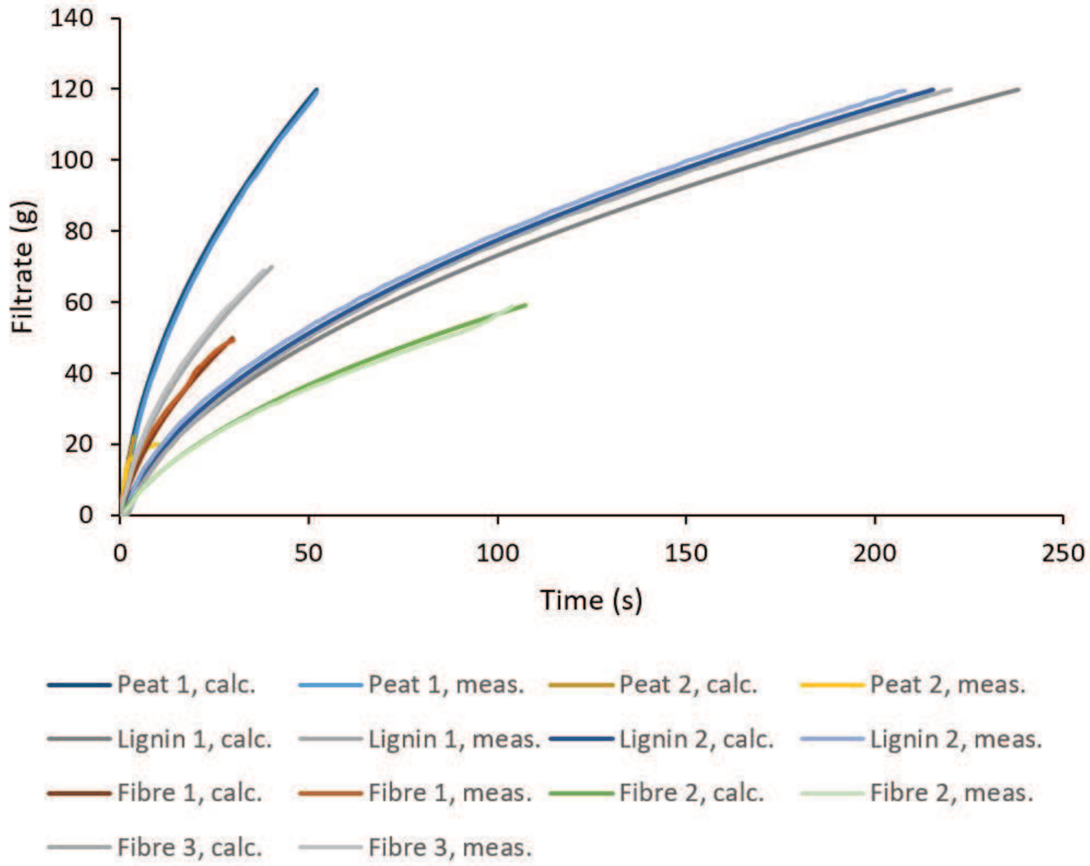


Figure 6.1 *Measured and calculated filtrate flux*

6.2 Modeling results

6.2.1 Model based on Kozeny-Carman

Particle size was analyzed between 0.01 - 10 000 μm by Malvern Mastersizer, which calculated the specific surface area from the particle size distribution assuming spherical particles. The results from the measurements were used straightly to calculate the specific cake resistance. The Kozeny-Carman equation, presented in Ch. 3.5.2, needs also a value for cake porosity, which was assumed to be 0.7. The resulted cake resistances compared to the resistance calculated from the filtration graphs are presented in a logarithmic scale in Fig. 6.2.

The calculated values do not show clear correlation with measured values. The cake resistance of Lignin 3 was unmeasurable, so the value of measured cake resistance

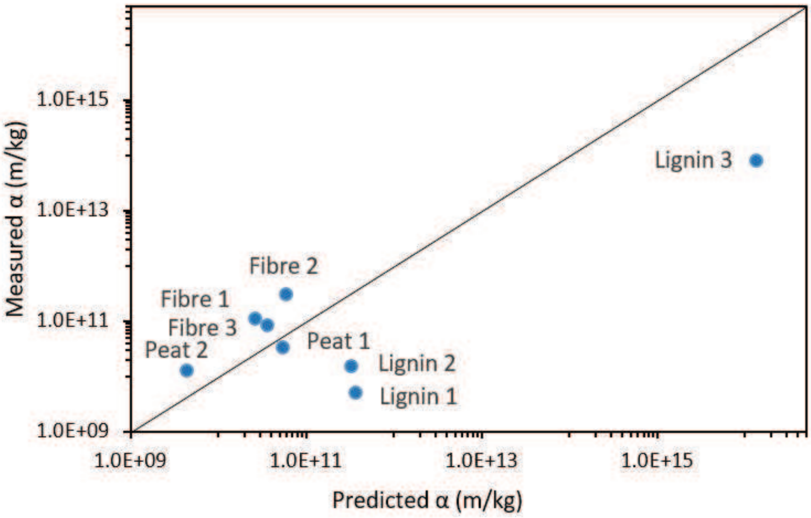


Figure 6.2 *Measured resistance vs. calculated resistance in Kozeny-Carman model*

is not fully accurate. Even though the measured value is an estimate, the calculated value also shows a great resistance value. With very small particles, the poor filterability can be predicted with the equation. If Lignin 3 is dismissed from the comparison, the correlation between measured and predicted values with the rest of the samples is poor. If also the rest two lignin samples are dismissed from the data, a small correlation between the rest of the samples do exist.

Also using actual porosity values measured from `FILTRATEST` caused poor correlation, even though slightly better than Figure 6.2 presents. This method causes the need to make another model for cake porosity, and even though the porosity could be calculated properly, the resulted resistance do not give good correlation. Therefore Kozeny-Carman equation is not discussed further, and it can be seen that slurry filterability with used substances can not be calculated with Kozeny-Carman equation.

6.2.2 Lumped model

Lumped model was created to give accurate resistance value for slurries investigated. The model was created by searching correlations between the variables, and taking the physical knowledge into account. The basis of the model is Sauter diameter, which is also used in Kozeny-Carman model presented before. The zeta-potential was squared, so the small differences between the values would be highlighted. The only major difference between lignin samples compared to the others was the conductivity, which was used to lower the resistance compared to the others.

The resulted specific resistance values compared to the measured values are presented in Fig. 6.3. The predicted values give quite good agreement with the measured values with the used substance. The particle sphericity was assumed to be 1 for all rounded particles, which includes all shapes excluding Fibre 1 and 2. For fibre samples, clearly fibrous shape with Fibre 1 was assumed to have sphericiy of 0.3 and less fibrous Fibre 2 was assumed to have sphericity of 0.6. The model gave adequate estimation of filterability with most of the used slurries. The only exceptions are both Peat slurries and Fibre 1, which have predicted resistance a bit too high.

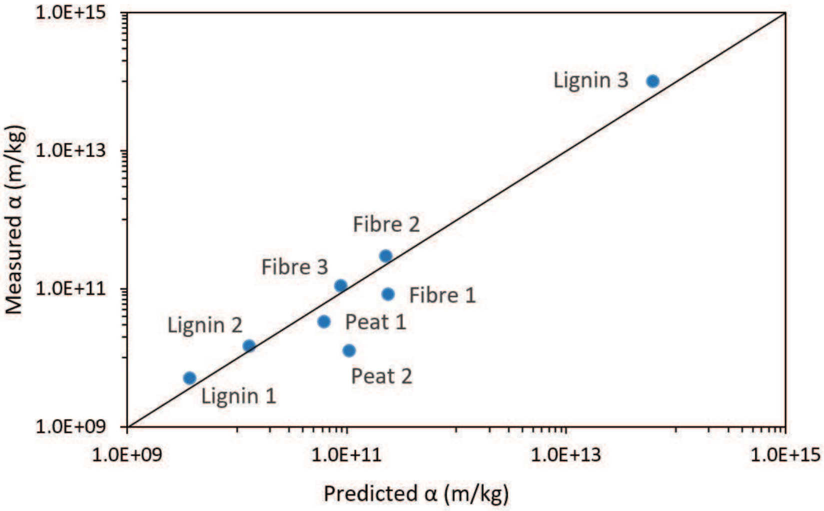


Figure 6.3 *Measured resistance vs. calculated resistance in the lumped model*

Nevertheless, though the model give good estimates of the filterability with used slurries, the model is unlikely to work as well with other substances. The value of specific cake resistance includes such complexity, that used parameters - Sauter diameter, zeta-potential, sphericity and conductivity - are unable to describe all different interactions in filterability. Also phenomenon such as filter cake or media clogging is not included to the model.

6.2.3 Linear regression model

Liner regression model is a statistical technique, where multiple predictors can be analyzed. Linear regression quantifies the relationship between two variables, and finds the best fit for a straight line between these two variables. The line is defined by an intercept and a slope. In multiple linear regression, each slope represents the effect of 1 variable controlled for all other variables in the model. [46]

Linear regression was calculated by using Excel^{TM} Tools. The variables added to the model were particle size presented by squared Sauter diameter, zeta-potential, conductivity and sphericity. The sphericities were assumed similarly than with Lumped model, Fibre 1 having sphericity of 0.3 and Fibre 2 having sphericity of 0.6. The regression statistics, Multiple R, R Square and standard error, which tell how strong the linearity is, can be read from Tab. 6.5.

Table 6.5 *Regression statistics*

	Regression statistics
Multiple R	0.9021
R Square	0.8139
Standard Error	1.110E+11

The slope used in linear regression is presented in Equation 6.1. In the equation, a is the intercept of the slope, b_1 the coefficient for X_1, b_2 coefficient for X_2 and so on. The equation is modified for this situation, as the total number of variables is equal to 5. The number of variables in the equation is the same as the number of variables in the data.

$$Y = a + b_1 * X_1 + b_2 * X_2 + b_3 * X_3 + b_4 * X_4 + b_5 * X_5, \tag{6.1}$$

The variables and calculated coefficient for each variable is presented in Table 6.6. The table includes also the standard error for each variable.

Table 6.6 *Regression coefficients*

	Coefficients	**Standard Error**
Intercept	-1.33E+12	1.28E+12
Solid density	5.73E+08	1.05E+09
Conductivity	-6.87E+09	8.74E+09
Zeta-potential	4.56E+10	2.76E+10
Specific surface area	8.63E+05	9.17E+05
Sphericity	1.37E+11	2.18E+11

The linear regression from the equation resulted gave negative cake resistance for Lignin 2, which can't be possible. For the other substances, the results seems reasonable. Figure 6.4 shows the calculated values from the linear regression model, together with measured values.

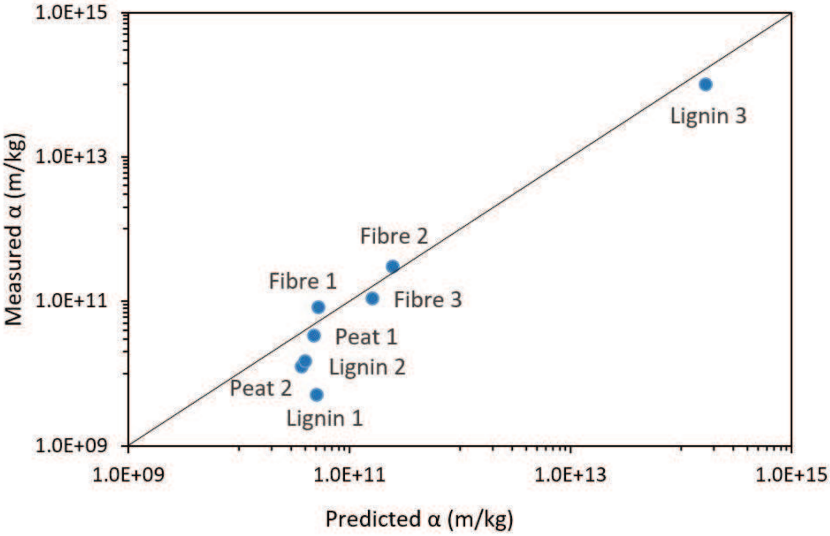


Figure 6.4 *Measured resistance vs. calculated resistance in the Linear regression model*

The correlation is better with linear model compared to the Kozeny-Carman model, but similar or even slightly poorer compared to the lumped model. The Lignin samples have predicted values much higher than the measured values, but also the other substances have some inaccuracy in the values. Since the model is based on linear regression, the resulted model give somehow unreliable results in certain situations, for example negative resistance values in certain case. Therefore the model should not be used for predicting filtration resistance.

Figure 6.5 shows the regression statistics for each variable used. From the plots shown, the relationship between each variable and resulted resistance can be seen. Quite surprisingly, the specific surface area, which is known to be a key parameter affecting on filtration efficiency, do not show a clear correlation with increasing resistance. Also solid density and sphericity do not give any clear correlation. Nevertheless, with zeta-potential, a weak correlation can be seen if the high resistance value with Lignin 3 is dismissed. Also small correlation with great conductivity value and small cake resistance do exist.

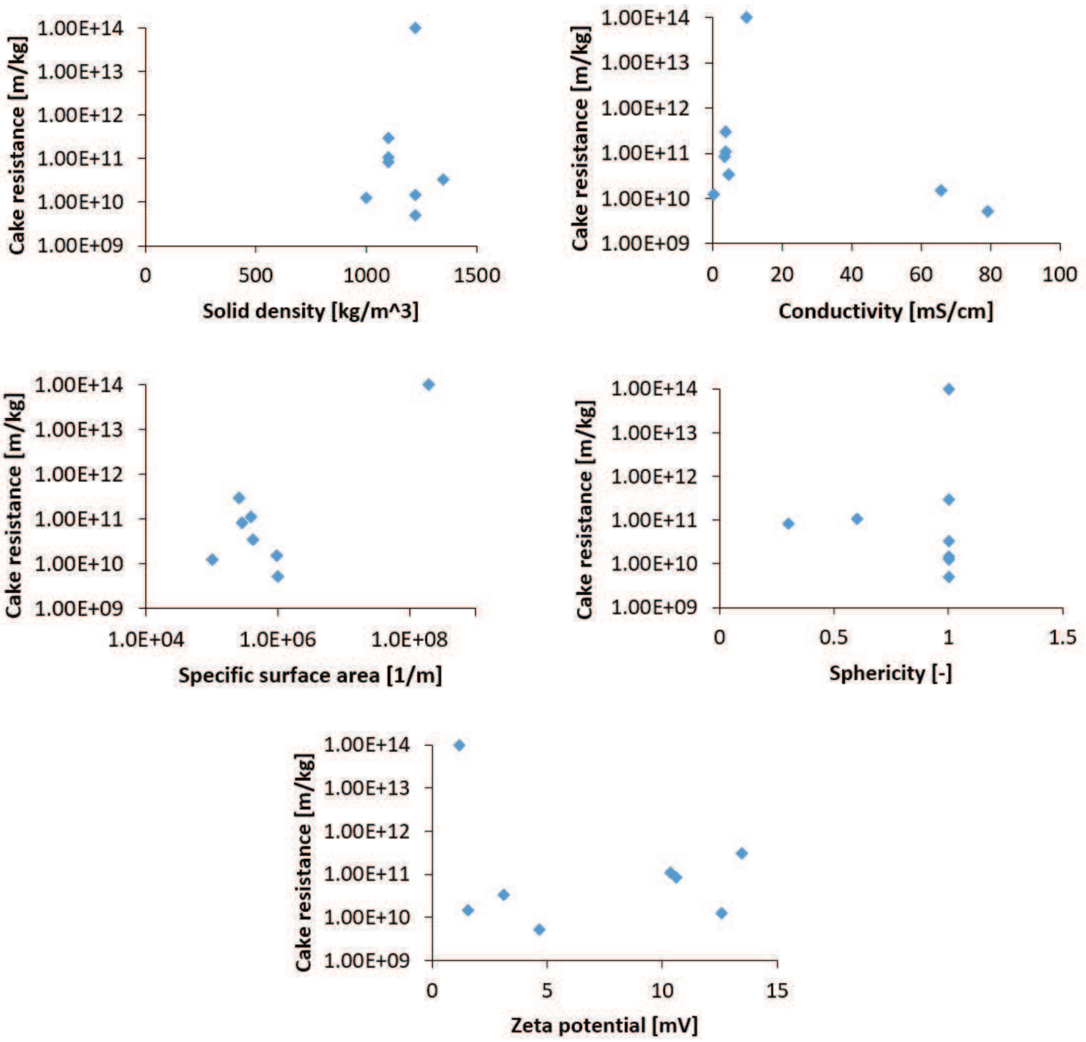


Figure 6.5 *Residual plots*

6.3 Effect of process variables

The effect of process variables, applied pressure p and temperature T, is investigated by comparing conventional filtration theory to the filtration results. The effect of temperature is assumed to depend only on liquid viscosity and density. With the effect of increasing pressure, the samples are firstly assumed to be incompressible. Nevertheless, if the slurries are found to be compressible, the compressibility index n is calculated.

The used temperature levels were 20, 45 and 65 °C. The viscosity value with most of the slurries was assumed equal to water viscosity. The values of water viscosity could be found from the literature. With lignin 1 and 2, the estimation of viscosities was gathered from initial data. Also liquid density changes with increasing temperature. The used viscosity and liquid density values in used temperatures are presented in Table 6.7. Viscosities μ are presented in unit Pa*s and densities ρ in kg/m^3.

Table 6.7 *Liquid viscosity and density in different temperatures*

Slurry	μ (20 °C)	μ (45 °C)	μ (65 °C)	ρ (20 °C)	ρ (45 °C)	ρ (65 °C)
Lignin 1	0.02	0.008	0.005	1225	1210	1197
Lignin 2	0.004	0.002	0.002	1135	1122	1110
Rest slurries	0.001	0.0006	0.0004	1000	9900	9800

In comparison of increased temperature, real cake resistance values are used. The filtrate flux is calculated, and filtration time when 120 g of received filtrate is compared. The samples presented are Lignin 1, lignin 2 and Peat slurry 1. The comparision between measured and calculated values when amount of filtrate received 120 g is presented in Figure 6.6.

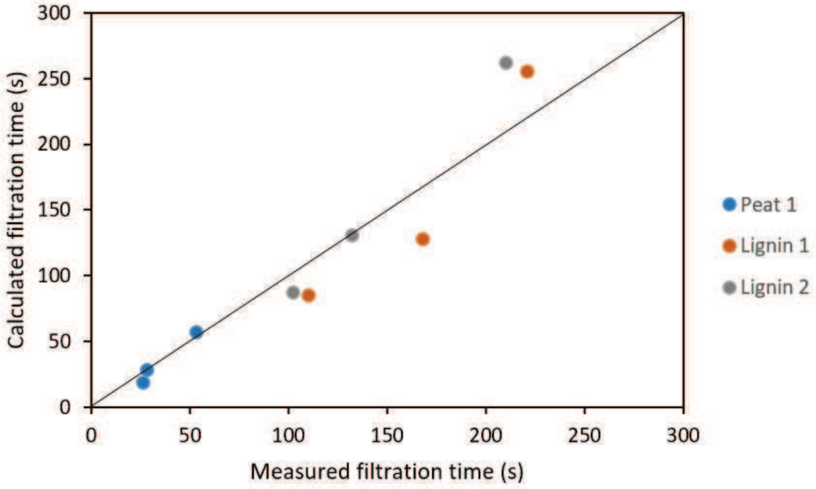


Figure 6.6 *Effect of increasing temperature*

The correlation between measured and calculated values is good with Peat 1, and also tolerable with lignin samples. Since the viscosities and densities of lignin samples is hard to measure due to non-Newtonian behavior, further assumptions of other variables affecting on filtration rate with increasing temperature cannot be made. The effect of increasing pressure was evaluated firstly just by changing the pressure from conventional filtration theory. Also non-compressible behavior was assumed. The results are presented in Figure 6.7. The Figure shows, that the assumption of non-compressive behavious is valid especially with Peat 1, but with both lignin samples, the effect of increasing pressure is not linear.

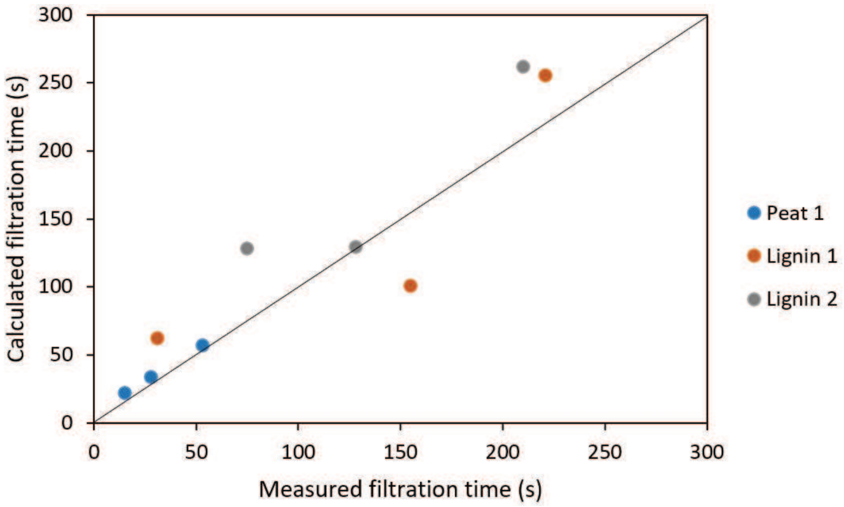


Figure 6.7 *Effect of increasing pressure*

7. CONCLUSIONS

The aim of this thesis was to create a model for predicting slurry filterability from collective slurry characteristics. The target was to find out, which slurry properties have the greatest effect on filtration efficiency, and investigate is it possible to predict filterability by measuring these properties. The investigation was done by literature review and experimental part. In the literature review the properties affecting to the filterability were defined based on previous investigations, and in the experimental part a test series including measurement of slurry properties and filtration tests was committed for eight biomass based slurries. Based on this data, models predicting slurry filterability were created. Also the effect of process variables, applied pressure and temperature, was included to the models.

Parameters affecting slurry filterability are particle properties such as particle size, shape, rigidity and density, liquid properties such as viscosity and density, slurry concentration, pH expressed usually by zeta-potential and different particle-particle and particle-liquid interactions such as surface tension forces. Also other interactions and filter media or cake clogging due to small or deformable particles have to be considered. Test series for comparing eight different slurries showed differences in filterability, and three models describing filterability were compared with each other. The first model introduced was the Kozeny-Carman model, which suitability for used slurries was tested. The model gave poor results with most of the slurries, and a correlation between measured and predicted values can not be seen. The second model, Lumped model, gave rather good correlation between the filterability. The last model was linear regression model, which gave a weak correlation. The modeling results are, that the created model gave better correlation that existing models. Nevertheless, the created model is questioned to work with other substances. Because of the complexity of the phenomenon, a perfect model for predicting slurry filterability couldn't be created. Instead, test series containing changes in process parameters, pressure and temperature, were in good agreement with conventional cake filtration theory. The actual effect of increasing temperature may affect also to the other slurry properties, such as surface tension forces, but with the used substances the correlation was adequate and further conclusions of effect of increasing temperature can not be made. With the effect of process parameters, similar results with other substances can not be assumed.

Numerous of reasons why predicting filterability from slurry characteristics is difficult does exists. First of all, it should be analyzed, are the slurry properties suitable for cake filtration. If even a few of the filter cloth pores are blocked, it might affect to the overall filtration efficiency. If enough particle bridging occurs, the actual filterability can be analyzed. A major difficultly is that cake porosity, which is known to have a remarkable role on filterability, can't be predicted with current knowledge. It is affected by mainly particle properties such as size and shape, but also particle interactions - pH and zeta-potential - affect on particle deposition in the filter cake. Also other properties, such as conductivity, have been reported to affect on filterability. It is also possible, that all chemical and physical properties affecting filterability have not been yet identificated. The widely-used method of comparing the filterability by using cake resistance parameter have received criticism for being inaccurate, but a more suitable way to define a slurry-specific parameter have not been invented. Also this lack of a reliable parameter comparing filterability with different slurries complicates the modeling.

Filtration remains mostly as an empirical science, where the laboratory measurements continue to describe the filterability, as the specific cake resistance cannot be evaluated accurately from the slurry data. More future research is needed especially considering particle interactions, which role in filterability have been recognized, but which have still limited understanding. The effect of cake and cloth blinding should be discussed further, also from the particle properties view. Nevertheless, modeling filtration can give important information of the process, and reduce the amount of tests made, if the modeling is done in a smaller scale. In current situation, creating modeling tools for each substance separately can be useful. For a certain slurry, for example effect of changes in particle size or effect of increasing pressure and temperature can be estimated from the modeling tool. Also modeling the effect of varying other filtration cycle parts, such as pressing and air-drying duration and pressure, gives information of how to design or improve the process.

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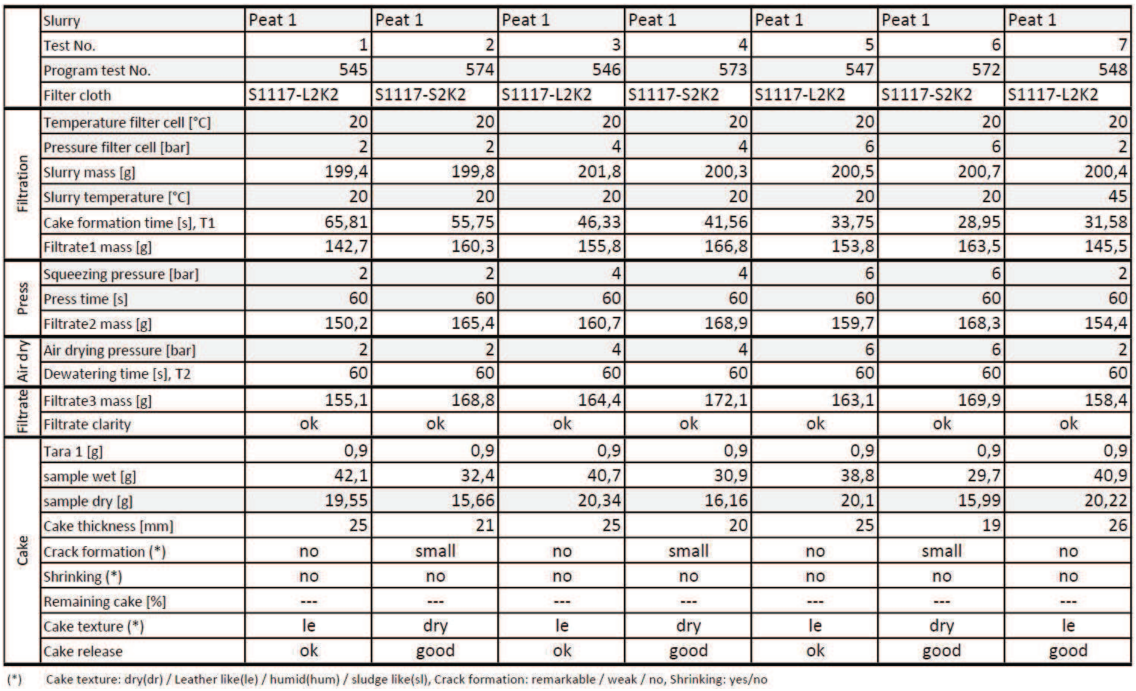
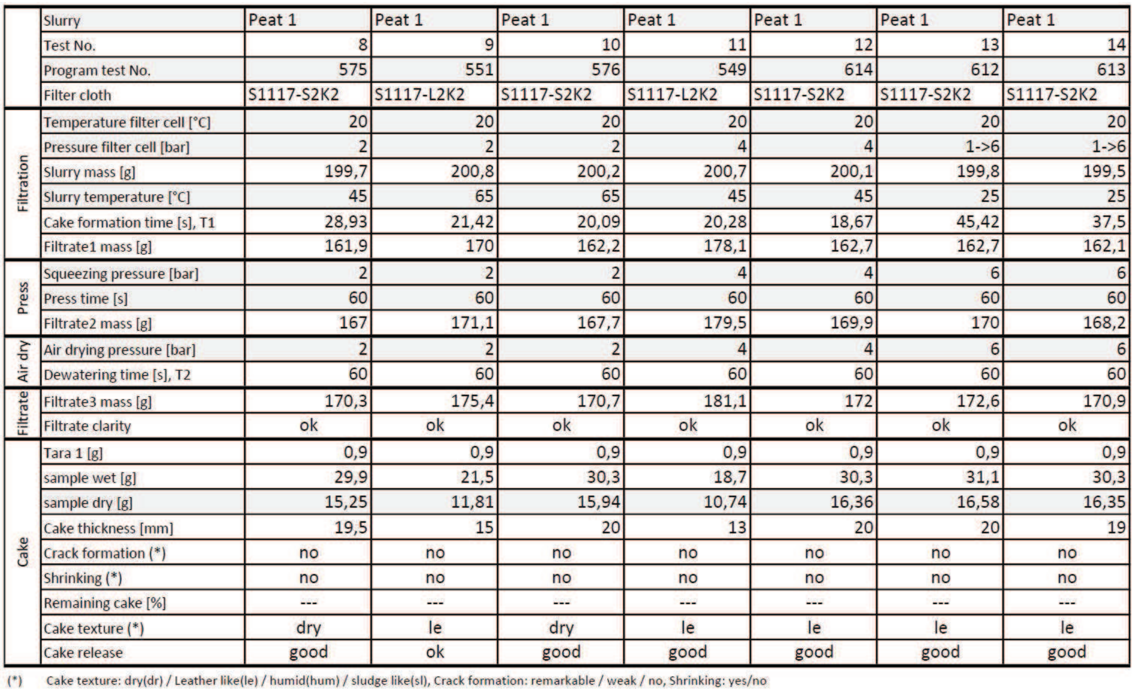
APPENDIX A. EXPERIMENTAL RESULTS



	Slurry	Peat 1	Peat 1	Peat 1	Peat 1	Peat 1	Peat 1	Peat 1
	Test No.	1	2	3	4	5	6	7
	Program test No.	545	574	546	573	547	572	548
	Filter cloth	S1117-L2K2	S1117-S2K2	S1117-L2K2	S1117-S2K2	S1117-L2K2	S1117-S2K2	S1117-L2K2
Filtration	Temperature filter cell [°C]	20	20	20	20	20	20	20
	Pressure filter cell [bar]	2	2	4	4	6	6	2
	Slurry mass [g]	199,4	199,8	201,8	200,3	200,5	200,7	200,4
	Slurry temperature [°C]	20	20	20	20	20	20	45
	Cake formation time [s], T1	65,81	55,75	46,33	41,56	33,75	28,95	31,58
	Filtrate1 mass [g]	142,7	160,3	155,8	166,8	153,8	163,5	145,5
Press	Squeezing pressure [bar]	2	2	4	4	6	6	2
	Press time [s]	60	60	60	60	60	60	60
	Filtrate2 mass [g]	150,2	165,4	160,7	168,9	159,7	168,3	154,4
Air dry	Air drying pressure [bar]	2	2	4	4	6	6	2
	Dewatering time [s], T2	60	60	60	60	60	60	60
Filtrate	Filtrate3 mass [g]	155,1	168,8	164,4	172,1	163,1	169,9	158,4
	Filtrate clarity	ok	ok	ok	ok	ok	ok	ok
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9	0,9	0,9
	sample wet [g]	42,1	32,4	40,7	30,9	38,8	29,7	40,9
	sample dry [g]	19,55	15,66	20,34	16,16	20,1	15,99	20,22
	Cake thickness [mm]	25	21	25	20	25	19	26
	Crack formation (*)	no	small	no	small	no	small	no
	Shrinking (*)	no	no	no	no	no	no	no
	Remaining cake [%]	---	---	---	---	---	---	---
	Cake texture (*)	le	dry	le	dry	le	dry	le
	Cake release	ok	good	ok	good	ok	good	good

(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

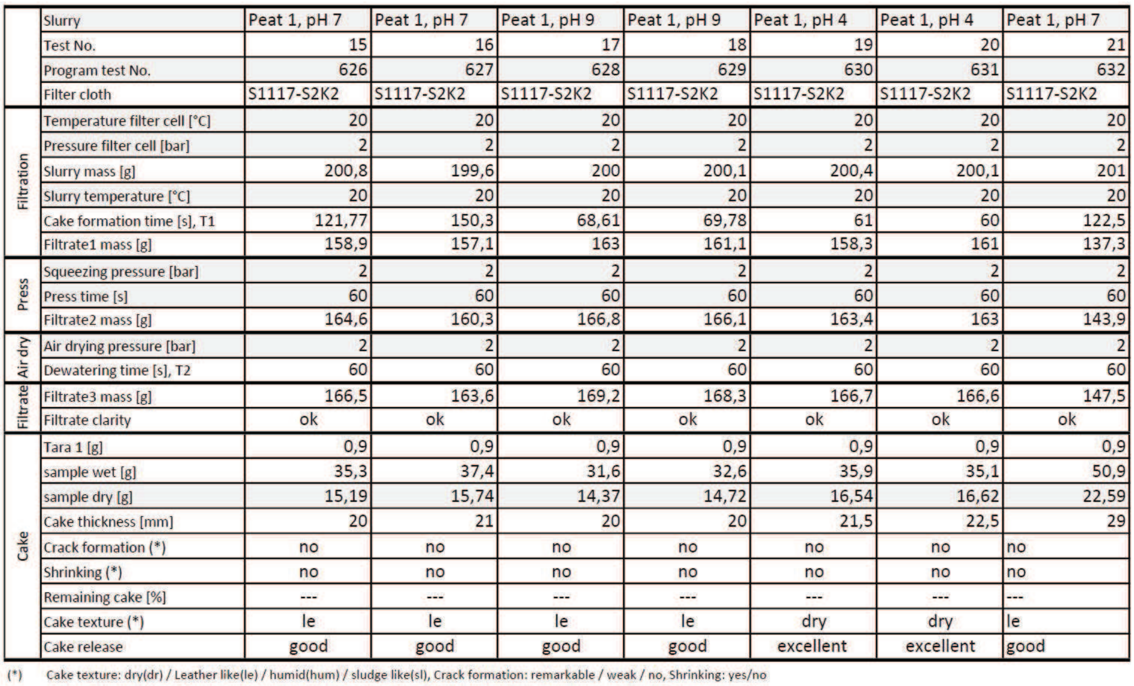
Experimental results for Peat 1



	Slurry	Peat 1	Peat 1	Peat 1	Peat 1	Peat 1	Peat 1	Peat 1
	Test No.	8	9	10	11	12	13	14
	Program test No.	575	551	576	549	614	612	613
	Filter cloth	S1117-S2K2	S1117-L2K2	S1117-S2K2	S1117-L2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2
Filtration	Temperature filter cell [°C]	20	20	20	20	20	20	20
	Pressure filter cell [bar]	2	2	2	4	4	1->6	1->6
	Slurry mass [g]	199,7	200,8	200,2	200,7	200,1	199,8	199,5
	Slurry temperature [°C]	45	65	65	45	45	25	25
	Cake formation time [s], T1	28,93	21,42	20,09	20,28	18,67	45,42	37,5
	Filtrate1 mass [g]	161,9	170	162,2	178,1	162,7	162,7	162,1
Press	Squeezing pressure [bar]	2	2	2	4	4	6	6
	Press time [s]	60	60	60	60	60	60	60
	Filtrate2 mass [g]	167	171,1	167,7	179,5	169,9	170	168,2
Air dry	Air drying pressure [bar]	2	2	2	4	4	6	6
	Dewatering time [s], T2	60	60	60	60	60	60	60
Filtrate	Filtrate3 mass [g]	170,3	175,4	170,7	181,1	172	172,6	170,9
	Filtrate clarity	ok	ok	ok	ok	ok	ok	ok
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9	0,9	0,9
	sample wet [g]	29,9	21,5	30,3	18,7	30,3	31,1	30,3
	sample dry [g]	15,25	11,81	15,94	10,74	16,36	16,58	16,35
	Cake thickness [mm]	19,5	15	20	13	20	20	19
	Crack formation (*)	no	no	no	no	no	no	no
	Shrinking (*)	no	no	no	no	no	no	no
	Remaining cake [%]	---	---	---	---	---	---	---
	Cake texture (*)	dry	le	dry	le	le	le	le
	Cake release	good	ok	good	good	good	good	good

(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

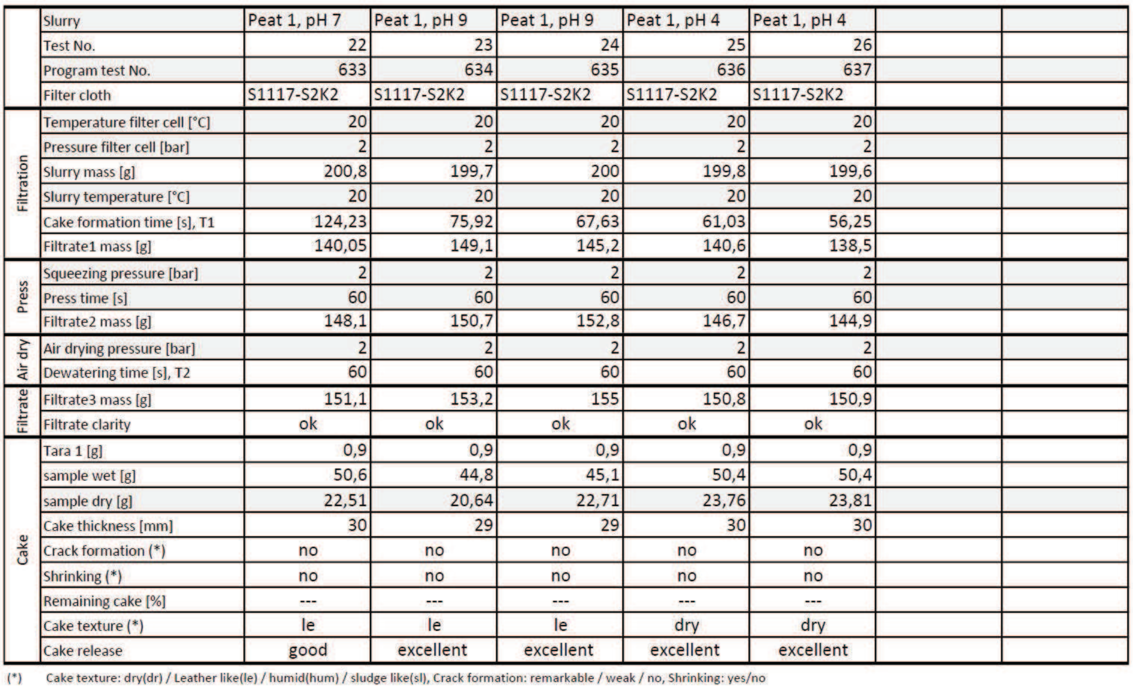
Experimental results for Peat 1



	Slurry	Peat 1, pH 7	Peat 1, pH 7	Peat 1, pH 9	Peat 1, pH 9	Peat 1, pH 4	Peat 1, pH 4	Peat 1, pH 7
	Test No.	15	16	17	18	19	20	21
	Program test No.	626	627	628	629	630	631	632
	Filter cloth	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2
Filtration	Temperature filter cell [°C]	20	20	20	20	20	20	20
	Pressure filter cell [bar]	2	2	2	2	2	2	2
	Slurry mass [g]	200,8	199,6	200	200,1	200,4	200,1	201
	Slurry temperature [°C]	20	20	20	20	20	20	20
	Cake formation time [s], T1	121,77	150,3	68,61	69,78	61	60	122,5
	Filtrate1 mass [g]	158,9	157,1	163	161,1	158,3	161	137,3
Press	Squeezing pressure [bar]	2	2	2	2	2	2	2
	Press time [s]	60	60	60	60	60	60	60
	Filtrate2 mass [g]	164,6	160,3	166,8	166,1	163,4	163	143,9
Air dry	Air drying pressure [bar]	2	2	2	2	2	2	2
	Dewatering time [s], T2	60	60	60	60	60	60	60
Filtrate	Filtrate3 mass [g]	166,5	163,6	169,2	168,3	166,7	166,6	147,5
	Filtrate clarity	ok	ok	ok	ok	ok	ok	ok
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9	0,9	0,9
	sample wet [g]	35,3	37,4	31,6	32,6	35,9	35,1	50,9
	sample dry [g]	15,19	15,74	14,37	14,72	16,54	16,62	22,59
	Cake thickness [mm]	20	21	20	20	21,5	22,5	29
	Crack formation (*)	no	no	no	no	no	no	no
	Shrinking (*)	no	no	no	no	no	no	no
	Remaining cake [%]	---	---	---	---	---	---	---
	Cake texture (*)	le	le	le	le	dry	dry	le
	Cake release	good	good	good	good	excellent	excellent	good

(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

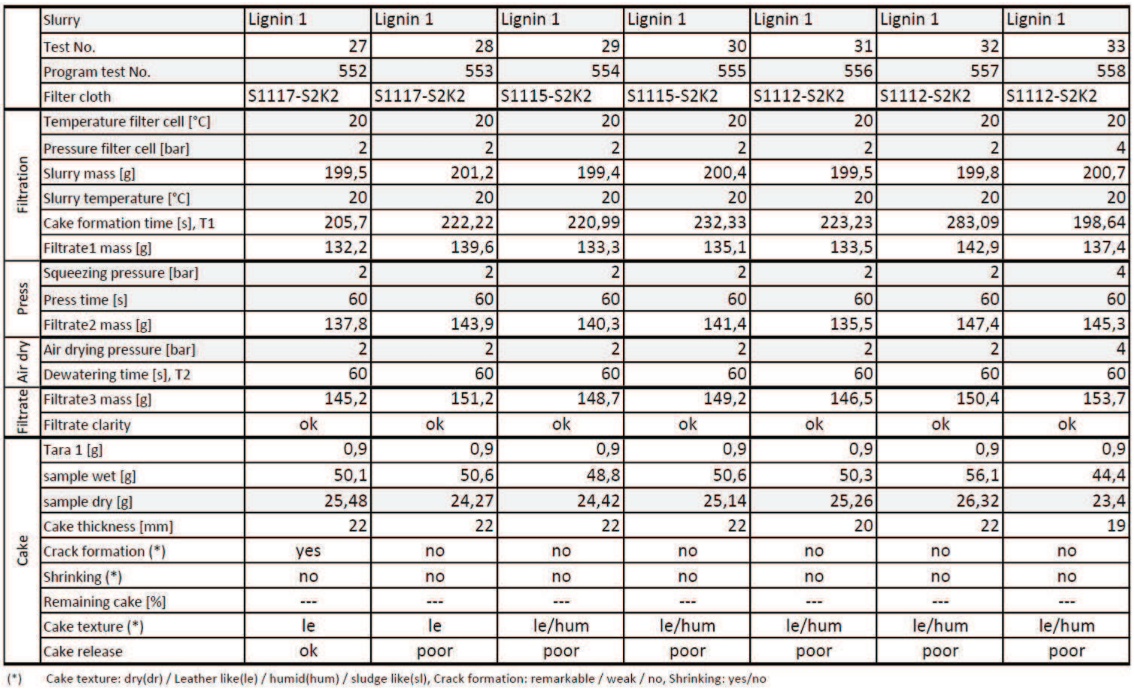
Experimental results for Peat 1



	Slurry	Peat 1, pH 7	Peat 1, pH 9	Peat 1, pH 9	Peat 1, pH 4	Peat 1, pH 4		
	Test No.	22	23	24	25	26		
	Program test No.	633	634	635	636	637		
	Filter cloth	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2		
Filtration	Temperature filter cell [°C]	20	20	20	20	20		
	Pressure filter cell [bar]	2	2	2	2	2		
	Slurry mass [g]	200,8	199,7	200	199,8	199,6		
	Slurry temperature [°C]	20	20	20	20	20		
	Cake formation time [s], T1	124,23	75,92	67,63	61,03	56,25		
	Filtrate1 mass [g]	140,05	149,1	145,2	140,6	138,5		
Press	Squeezing pressure [bar]	2	2	2	2	2		
	Press time [s]	60	60	60	60	60		
	Filtrate2 mass [g]	148,1	150,7	152,8	146,7	144,9		
Air dry	Air drying pressure [bar]	2	2	2	2	2		
	Dewatering time [s], T2	60	60	60	60	60		
Filtrate	Filtrate3 mass [g]	151,1	153,2	155	150,8	150,9		
	Filtrate clarity	ok	ok	ok	ok	ok		
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9		
	sample wet [g]	50,6	44,8	45,1	50,4	50,4		
	sample dry [g]	22,51	20,64	22,71	23,76	23,81		
	Cake thickness [mm]	30	29	29	30	30		
	Crack formation (*)	no	no	no	no	no		
	Shrinking (*)	no	no	no	no	no		
	Remaining cake [%]	---	---	---	---	---		
	Cake texture (*)	le	le	le	dry	dry		
	Cake release	good	excellent	excellent	excellent	excellent		

(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

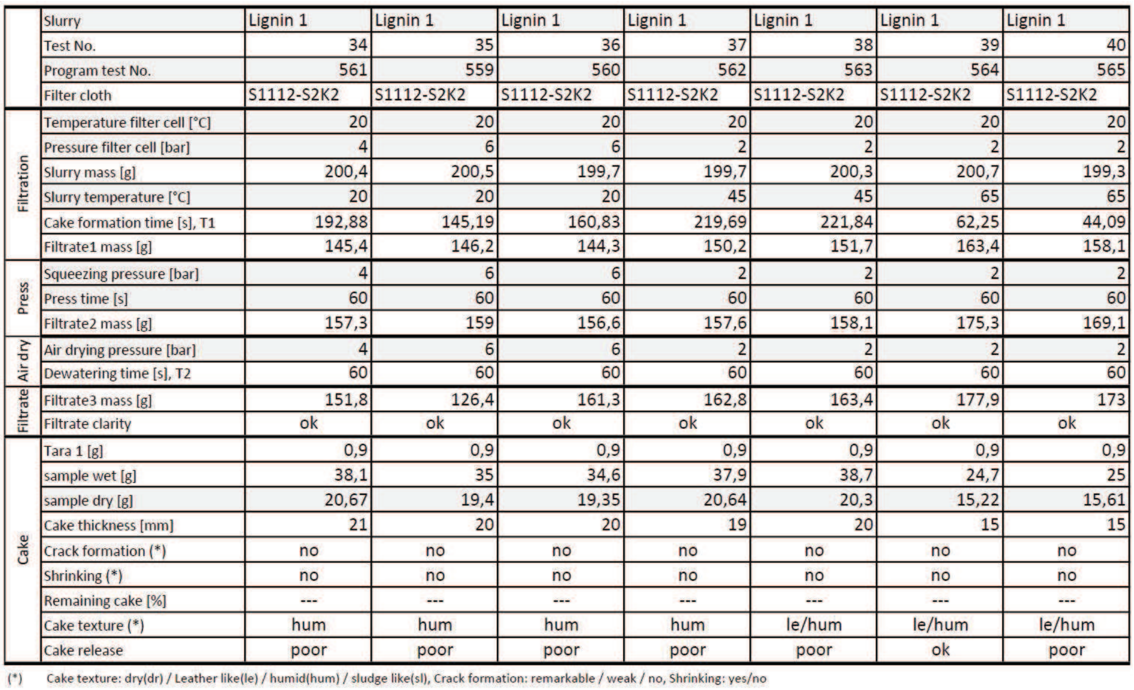
Experimental results for Peat 1



	Slurry	Lignin 1	Lignin 1	Lignin 1	Lignin 1	Lignin 1	Lignin 1	Lignin 1
	Test No.	27	28	29	30	31	32	33
	Program test No.	552	553	554	555	556	557	558
	Filter cloth	S1117-S2K2	S1117-S2K2	S1115-S2K2	S1115-S2K2	S1112-S2K2	S1112-S2K2	S1112-S2K2
Filtration	Temperature filter cell [°C]	20	20	20	20	20	20	20
	Pressure filter cell [bar]	2	2	2	2	2	2	4
	Slurry mass [g]	199,5	201,2	199,4	200,4	199,5	199,8	200,7
	Slurry temperature [°C]	20	20	20	20	20	20	20
	Cake formation time [s], T1	205,7	222,22	220,99	232,33	223,23	283,09	198,64
	Filtrate1 mass [g]	132,2	139,6	133,3	135,1	133,5	142,9	137,4
Press	Squeezing pressure [bar]	2	2	2	2	2	2	4
	Press time [s]	60	60	60	60	60	60	60
	Filtrate2 mass [g]	137,8	143,9	140,3	141,4	135,5	147,4	145,3
Air dry	Air drying pressure [bar]	2	2	2	2	2	2	4
	Dewatering time [s], T2	60	60	60	60	60	60	60
Filtrate	Filtrate3 mass [g]	145,2	151,2	148,7	149,2	146,5	150,4	153,7
	Filtrate clarity	ok	ok	ok	ok	ok	ok	ok
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9	0,9	0,9
	sample wet [g]	50,1	50,6	48,8	50,6	50,3	56,1	44,4
	sample dry [g]	25,48	24,27	24,42	25,14	25,26	26,32	23,4
	Cake thickness [mm]	22	22	22	22	20	22	19
	Crack formation (*)	yes	no	no	no	no	no	no
	Shrinking (*)	no	no	no	no	no	no	no
	Remaining cake [%]	---	---	---	---	---	---	---
	Cake texture (*)	le	le	le/hum	le/hum	le/hum	le/hum	le/hum
	Cake release	ok	poor	poor	poor	poor	poor	poor

(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

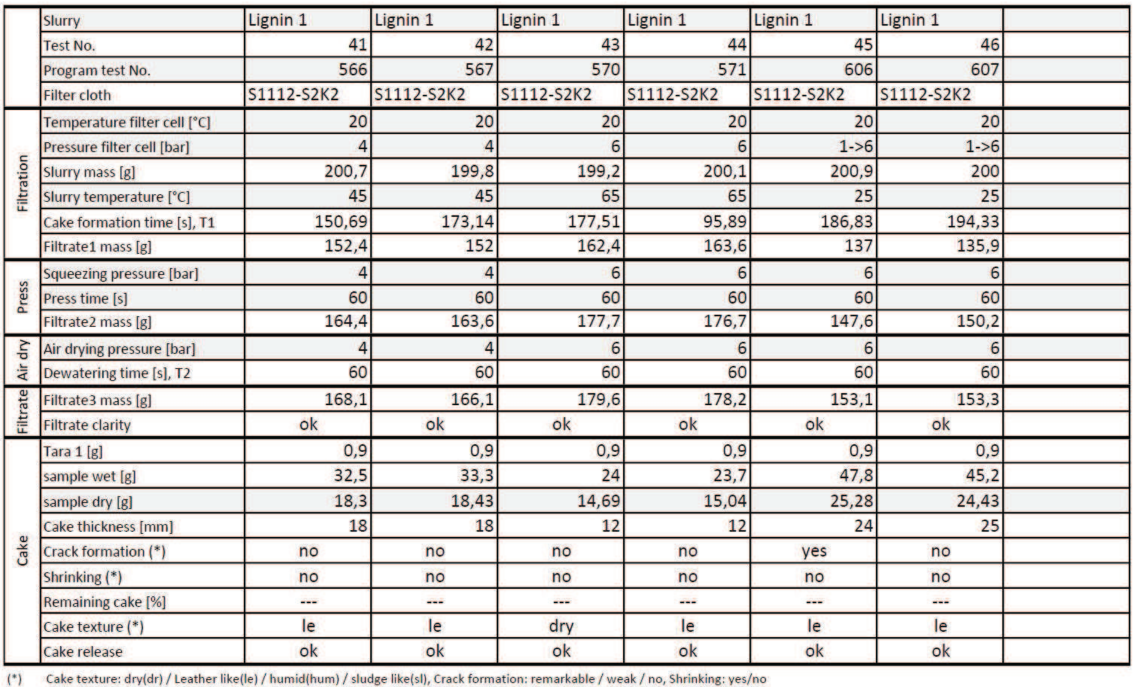
Experimental results for Lignin 1



	Slurry	Lignin 1	Lignin 1	Lignin 1	Lignin 1	Lignin 1	Lignin 1	Lignin 1
	Test No.	34	35	36	37	38	39	40
	Program test No.	561	559	560	562	563	564	565
	Filter cloth	S1112-S2K2	S1112-S2K2	S1112-S2K2	S1112-S2K2	S1112-S2K2	S1112-S2K2	S1112-S2K2
Filtration	Temperature filter cell [°C]	20	20	20	20	20	20	20
	Pressure filter cell [bar]	4	6	6	2	2	2	2
	Slurry mass [g]	200,4	200,5	199,7	199,7	200,3	200,7	199,3
	Slurry temperature [°C]	20	20	20	45	45	65	65
	Cake formation time [s], T1	192,88	145,19	160,83	219,69	221,84	62,25	44,09
	Filtrate1 mass [g]	145,4	146,2	144,3	150,2	151,7	163,4	158,1
Press	Squeezing pressure [bar]	4	6	6	2	2	2	2
	Press time [s]	60	60	60	60	60	60	60
	Filtrate2 mass [g]	157,3	159	156,6	157,6	158,1	175,3	169,1
Air dry	Air drying pressure [bar]	4	6	6	2	2	2	2
	Dewatering time [s], T2	60	60	60	60	60	60	60
Filtrate	Filtrate3 mass [g]	151,8	126,4	161,3	162,8	163,4	177,9	173
	Filtrate clarity	ok	ok	ok	ok	ok	ok	ok
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9	0,9	0,9
	sample wet [g]	38,1	35	34,6	37,9	38,7	24,7	25
	sample dry [g]	20,67	19,4	19,35	20,64	20,3	15,22	15,61
	Cake thickness [mm]	21	20	20	19	20	15	15
	Crack formation (*)	no	no	no	no	no	no	no
	Shrinking (*)	no	no	no	no	no	no	no
	Remaining cake [%]	---	---	---	---	---	---	---
	Cake texture (*)	hum	hum	hum	hum	le/hum	le/hum	le/hum
	Cake release	poor	poor	poor	poor	poor	ok	poor

(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

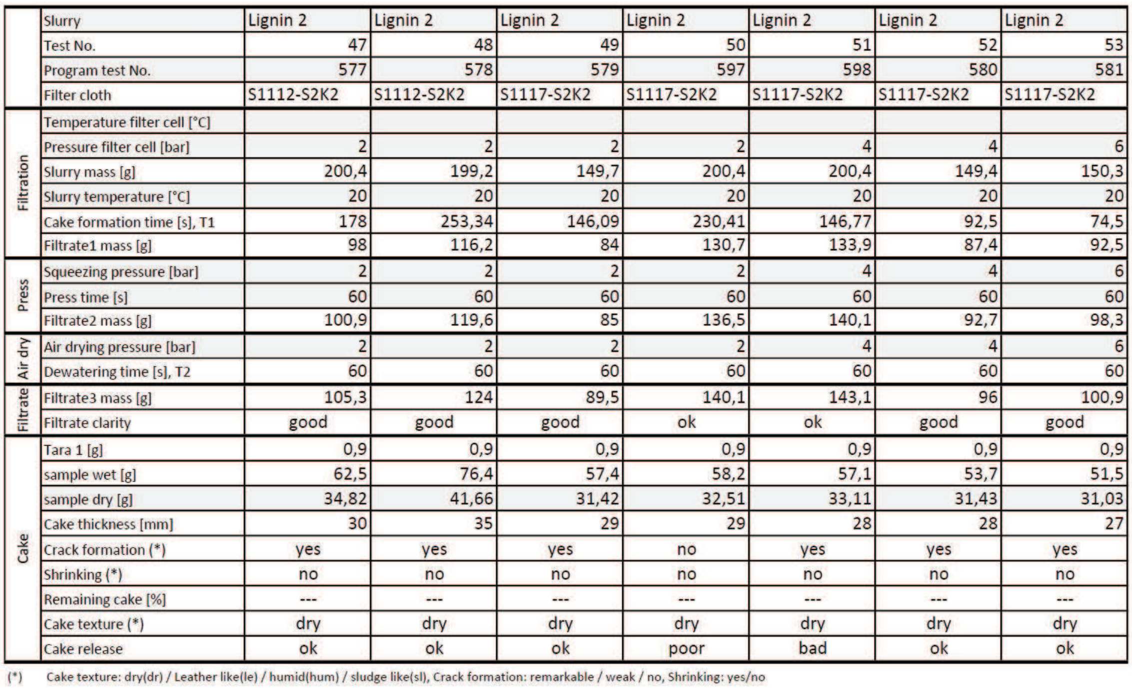
Experimental results for Lignin 1



	Slurry	Lignin 1	Lignin 1	Lignin 1	Lignin 1	Lignin 1	Lignin 1	
	Test No.	41	42	43	44	45	46	
	Program test No.	566	567	570	571	606	607	
	Filter cloth	S1112-S2K2	S1112-S2K2	S1112-S2K2	S1112-S2K2	S1112-S2K2	S1112-S2K2	
Filtration	Temperature filter cell [°C]	20	20	20	20	20	20	
	Pressure filter cell [bar]	4	4	6	6	1->6	1->6	
	Slurry mass [g]	200,7	199,8	199,2	200,1	200,9	200	
	Slurry temperature [°C]	45	45	65	65	25	25	
	Cake formation time [s], T1	150,69	173,14	177,51	95,89	186,83	194,33	
	Filtrate1 mass [g]	152,4	152	162,4	163,6	137	135,9	
Press	Squeezing pressure [bar]	4	4	6	6	6	6	
	Press time [s]	60	60	60	60	60	60	
	Filtrate2 mass [g]	164,4	163,6	177,7	176,7	147,6	150,2	
Air dry	Air drying pressure [bar]	4	4	6	6	6	6	
	Dewatering time [s], T2	60	60	60	60	60	60	
Filtrate	Filtrate3 mass [g]	168,1	166,1	179,6	178,2	153,1	153,3	
	Filtrate clarity	ok	ok	ok	ok	ok	ok	
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9	0,9	
	sample wet [g]	32,5	33,3	24	23,7	47,8	45,2	
	sample dry [g]	18,3	18,43	14,69	15,04	25,28	24,43	
	Cake thickness [mm]	18	18	12	12	24	25	
	Crack formation (*)	no	no	no	no	yes	no	
	Shrinking (*)	no	no	no	no	no	no	
	Remaining cake [%]	---	---	---	---	---	---	
	Cake texture (*)	le	le	dry	le	le	le	
	Cake release	ok	ok	ok	ok	ok	ok	

(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

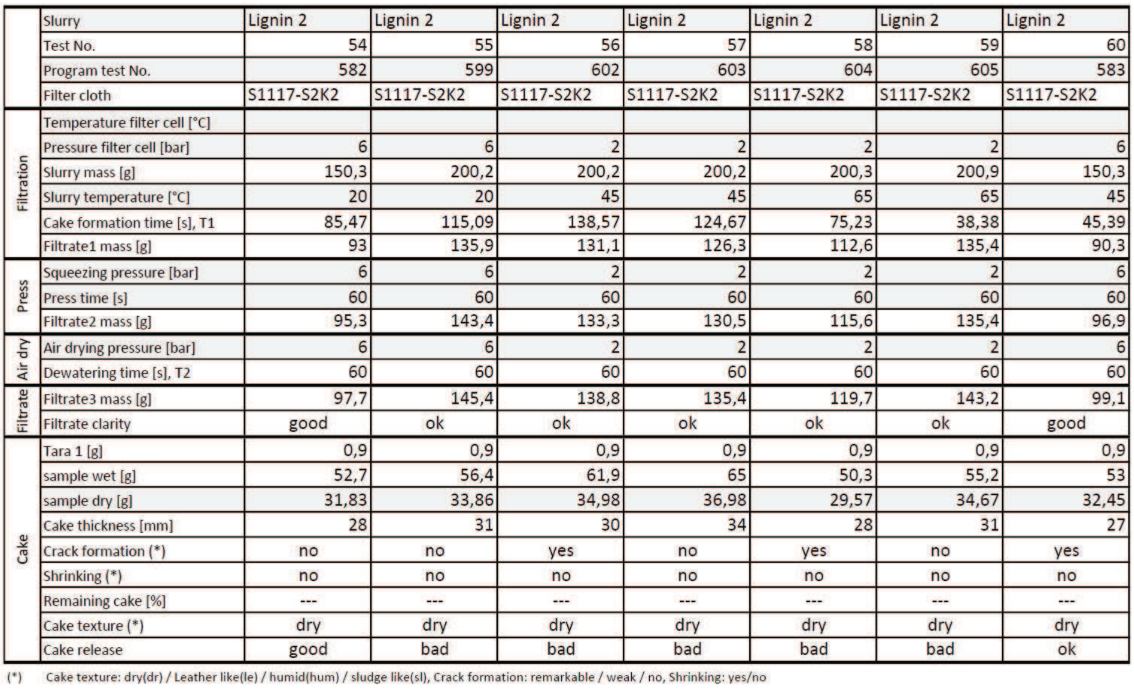
Experimental results for Lignin 1



	Slurry	Lignin 2	Lignin 2	Lignin 2	Lignin 2	Lignin 2	Lignin 2	Lignin 2
	Test No.	47	48	49	50	51	52	53
	Program test No.	577	578	579	597	598	580	581
	Filter cloth	S1112-S2K2	S1112-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2
Filtration	Temperature filter cell [°C]							
	Pressure filter cell [bar]	2	2	2	2	4	4	6
	Slurry mass [g]	200,4	199,2	149,7	200,4	200,4	149,4	150,3
	Slurry temperature [°C]	20	20	20	20	20	20	20
	Cake formation time [s], T1	178	253,34	146,09	230,41	146,77	92,5	74,5
	Filtrate1 mass [g]	98	116,2	84	130,7	133,9	87,4	92,5
Press	Squeezing pressure [bar]	2	2	2	2	4	4	6
	Press time [s]	60	60	60	60	60	60	60
	Filtrate2 mass [g]	100,9	119,6	85	136,5	140,1	92,7	98,3
Air dry	Air drying pressure [bar]	2	2	2	2	4	4	6
	Dewatering time [s], T2	60	60	60	60	60	60	60
Filtrate	Filtrate3 mass [g]	105,3	124	89,5	140,1	143,1	96	100,9
	Filtrate clarity	good	good	good	ok	ok	good	good
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9	0,9	0,9
	sample wet [g]	62,5	76,4	57,4	58,2	57,1	53,7	51,5
	sample dry [g]	34,82	41,66	31,42	32,51	33,11	31,43	31,03
	Cake thickness [mm]	30	35	29	29	28	28	27
	Crack formation (*)	yes	yes	yes	no	yes	yes	yes
	Shrinking (*)	no	no	no	no	no	no	no
	Remaining cake [%]	---	---	---	---	---	---	---
	Cake texture (*)	dry	dry	dry	dry	dry	dry	dry
	Cake release	ok	ok	ok	poor	bad	ok	ok

(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

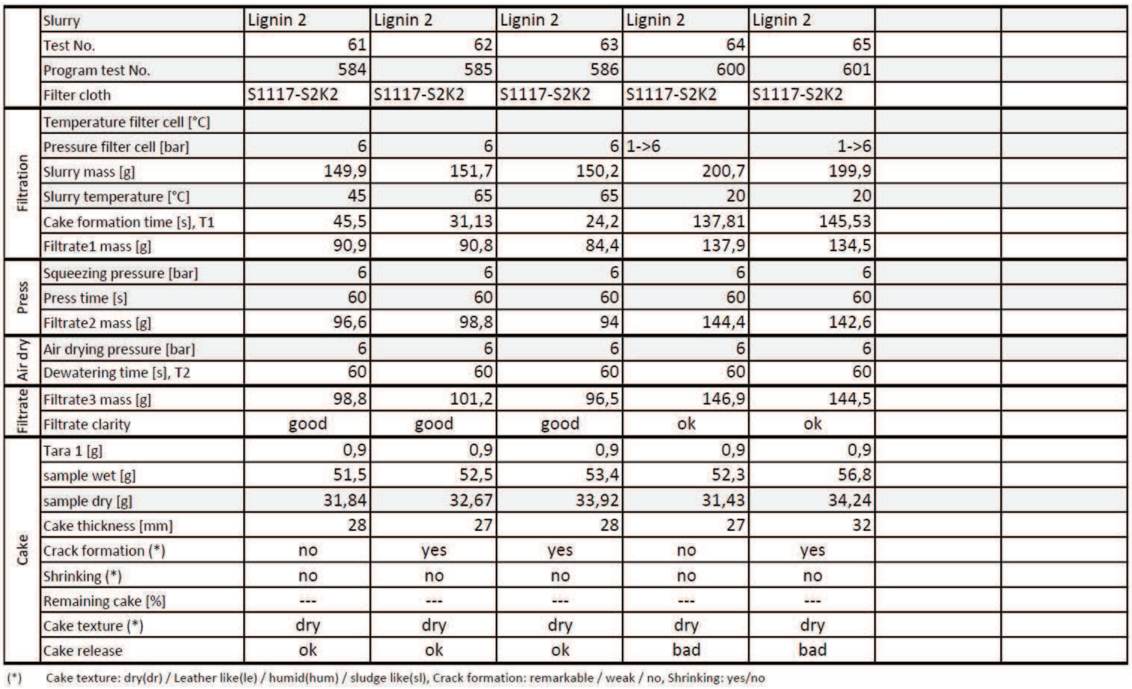
Experimental results for Lignin 1



	Slurry	Lignin 2	Lignin 2	Lignin 2	Lignin 2	Lignin 2	Lignin 2	Lignin 2
	Test No.	54	55	56	57	58	59	60
	Program test No.	582	599	602	603	604	605	583
	Filter cloth	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2
Filtration	Temperature filter cell [°C]							
	Pressure filter cell [bar]	6	6	2	2	2	2	6
	Slurry mass [g]	150,3	200,2	200,2	200,2	200,3	200,9	150,3
	Slurry temperature [°C]	20	20	45	45	65	65	45
	Cake formation time [s], T1	85,47	115,09	138,57	124,67	75,23	38,38	45,39
	Filtrate1 mass [g]	93	135,9	131,1	126,3	112,6	135,4	90,3
Press	Squeezing pressure [bar]	6	6	2	2	2	2	6
	Press time [s]	60	60	60	60	60	60	60
	Filtrate2 mass [g]	95,3	143,4	133,3	130,5	115,6	135,4	96,9
Air dry	Air drying pressure [bar]	6	6	2	2	2	2	6
	Dewatering time [s], T2	60	60	60	60	60	60	60
Filtrate	Filtrate3 mass [g]	97,7	145,4	138,8	135,4	119,7	143,2	99,1
	Filtrate clarity	good	ok	ok	ok	ok	ok	good
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9	0,9	0,9
	sample wet [g]	52,7	56,4	61,9	65	50,3	55,2	53
	sample dry [g]	31,83	33,86	34,98	36,98	29,57	34,67	32,45
	Cake thickness [mm]	28	31	30	34	28	31	27
	Crack formation (*)	no	no	yes	no	yes	no	yes
	Shrinking (*)	no	no	no	no	no	no	no
	Remaining cake [%]	---	---	---	---	---	---	---
	Cake texture (*)	dry	dry	dry	dry	dry	dry	dry
	Cake release	good	bad	bad	bad	bad	bad	ok

(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

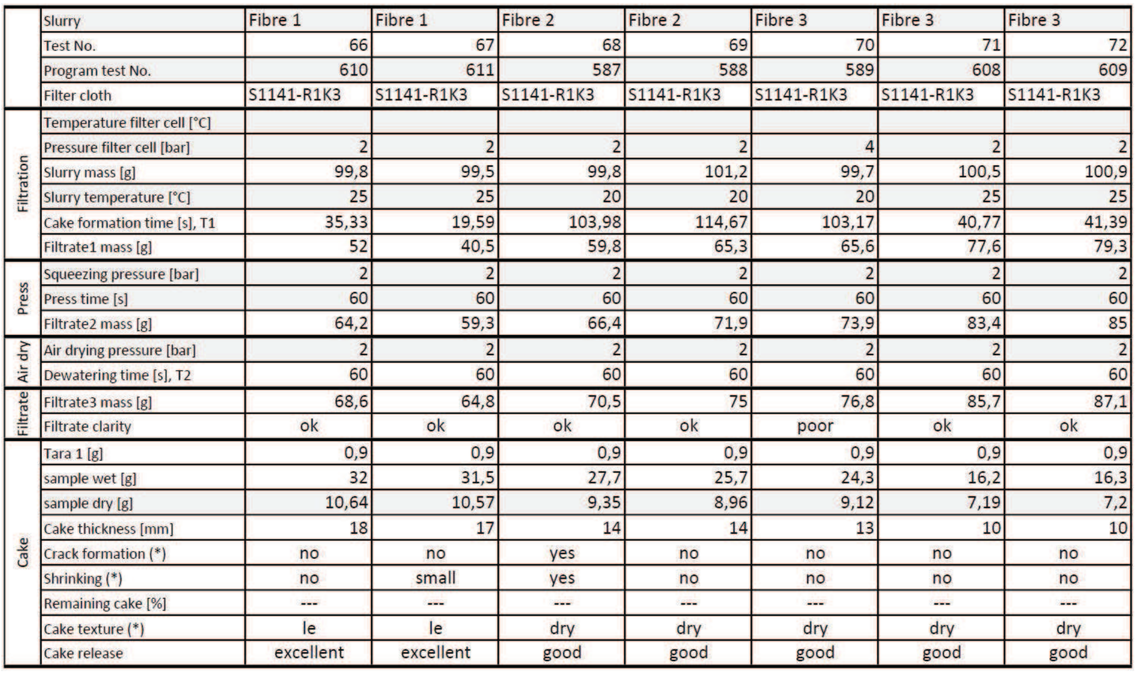
Experimental results for Lignin 2



	Slurry	Lignin 2	Lignin 2	Lignin 2	Lignin 2	Lignin 2		
	Test No.	61	62	63	64	65		
	Program test No.	584	585	586	600	601		
	Filter cloth	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2	S1117-S2K2		
Filtration	Temperature filter cell [°C]							
	Pressure filter cell [bar]	6	6	6	1->6	1->6		
	Slurry mass [g]	149,9	151,7	150,2	200,7	199,9		
	Slurry temperature [°C]	45	65	65	20	20		
	Cake formation time [s], T1	45,5	31,13	24,2	137,81	145,53		
	Filtrate1 mass [g]	90,9	90,8	84,4	137,9	134,5		
Press	Squeezing pressure [bar]	6	6	6	6	6		
	Press time [s]	60	60	60	60	60		
	Filtrate2 mass [g]	96,6	98,8	94	144,4	142,6		
Air dry	Air drying pressure [bar]	6	6	6	6	6		
	Dewatering time [s], T2	60	60	60	60	60		
Filtrate	Filtrate3 mass [g]	98,8	101,2	96,5	146,9	144,5		
	Filtrate clarity	good	good	good	ok	ok		
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9		
	sample wet [g]	51,5	52,5	53,4	52,3	56,8		
	sample dry [g]	31,84	32,67	33,92	31,43	34,24		
	Cake thickness [mm]	28	27	28	27	32		
	Crack formation (*)	no	yes	yes	no	yes		
	Shrinking (*)	no	no	no	no	no		
	Remaining cake [%]	---	---	---	---	---		
	Cake texture (*)	dry	dry	dry	dry	dry		
	Cake release	ok	ok	ok	bad	bad		

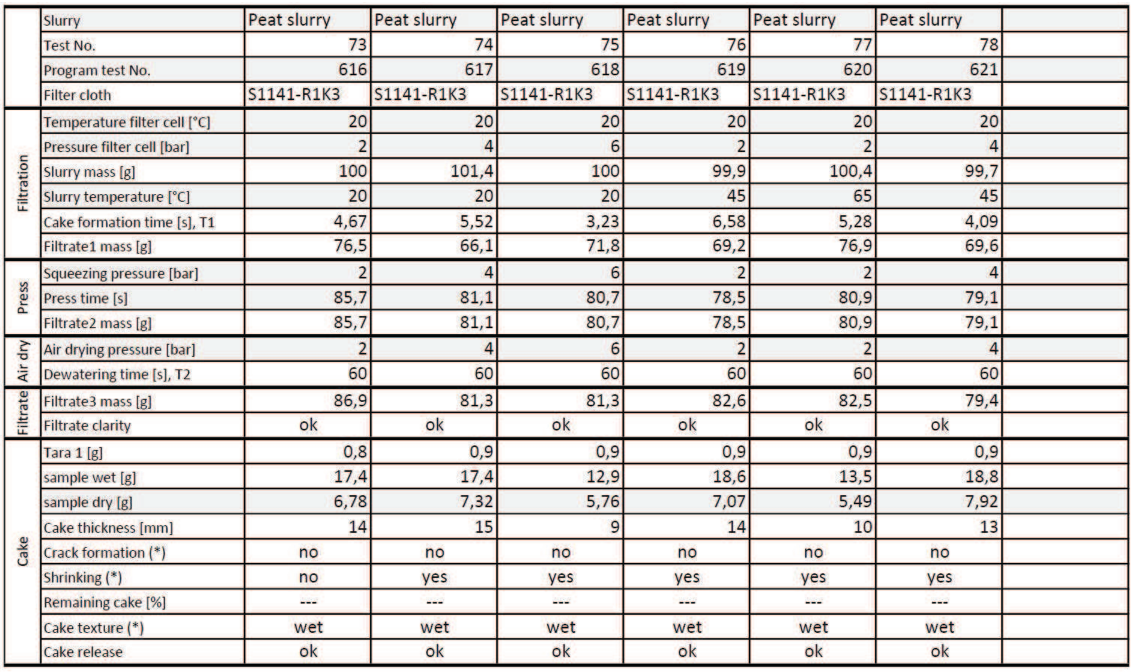
(*) Cake texture: dry(dr) / Leather like(le) / humid(hum) / sludge like(sl), Crack formation: remarkable / weak / no, Shrinking: yes/no

Experimental results for Lignin 2



	Slurry	Fibre 1	Fibre 1	Fibre 2	Fibre 2	Fibre 3	Fibre 3	Fibre 3
	Test No.	66	67	68	69	70	71	72
	Program test No.	610	611	587	588	589	608	609
	Filter cloth	S1141-R1K3	S1141-R1K3	S1141-R1K3	S1141-R1K3	S1141-R1K3	S1141-R1K3	S1141-R1K3
Filtration	Temperature filter cell [°C]							
	Pressure filter cell [bar]	2	2	2	2	4	2	2
	Slurry mass [g]	99,8	99,5	99,8	101,2	99,7	100,5	100,9
	Slurry temperature [°C]	25	25	20	20	20	25	25
	Cake formation time [s], T1	35,33	19,59	103,98	114,67	103,17	40,77	41,39
	Filtrate1 mass [g]	52	40,5	59,8	65,3	65,6	77,6	79,3
Press	Squeezing pressure [bar]	2	2	2	2	2	2	2
	Press time [s]	60	60	60	60	60	60	60
	Filtrate2 mass [g]	64,2	59,3	66,4	71,9	73,9	83,4	85
Air dry	Air drying pressure [bar]	2	2	2	2	2	2	2
	Dewatering time [s], T2	60	60	60	60	60	60	60
Filtrate	Filtrate3 mass [g]	68,6	64,8	70,5	75	76,8	85,7	87,1
	Filtrate clarity	ok	ok	ok	ok	poor	ok	ok
Cake	Tara 1 [g]	0,9	0,9	0,9	0,9	0,9	0,9	0,9
	sample wet [g]	32	31,5	27,7	25,7	24,3	16,2	16,3
	sample dry [g]	10,64	10,57	9,35	8,96	9,12	7,19	7,2
	Cake thickness [mm]	18	17	14	14	13	10	10
	Crack formation (*)	no	no	yes	no	no	no	no
	Shrinking (*)	no	small	yes	no	no	no	no
	Remaining cake [%]	---	---	---	---	---	---	---
	Cake texture (*)	le	le	dry	dry	dry	dry	dry
	Cake release	excellent	excellent	good	good	good	good	good

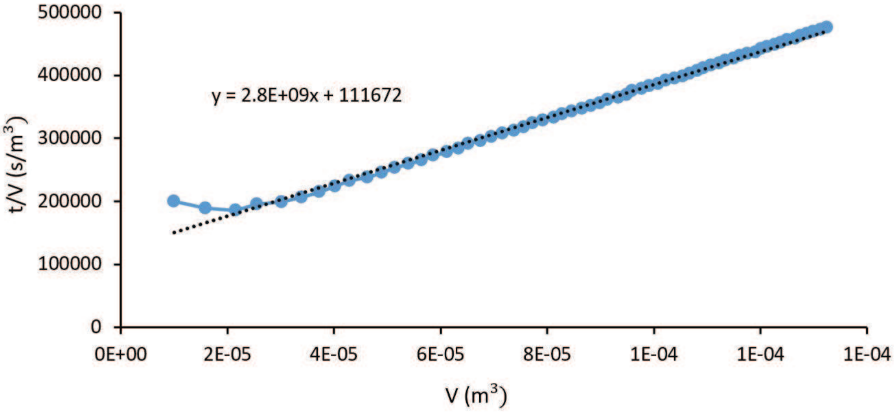
Experimental results for Fibres 1, 2 and 3



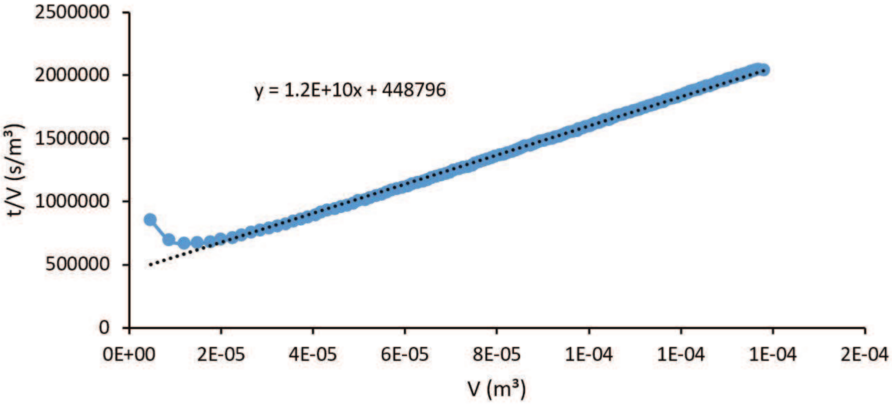
	Slurry	Peat slurry	Peat slurry	Peat slurry	Peat slurry	Peat slurry	Peat slurry	
	Test No.	73	74	75	76	77	78	
	Program test No.	616	617	618	619	620	621	
	Filter cloth	S1141-R1K3	S1141-R1K3	S1141-R1K3	S1141-R1K3	S1141-R1K3	S1141-R1K3	
Filtration	Temperature filter cell [°C]	20	20	20	20	20	20	
	Pressure filter cell [bar]	2	4	6	2	2	4	
	Slurry mass [g]	100	101,4	100	99,9	100,4	99,7	
	Slurry temperature [°C]	20	20	20	45	65	45	
	Cake formation time [s], T1	4,67	5,52	3,23	6,58	5,28	4,09	
	Filtrate1 mass [g]	76,5	66,1	71,8	69,2	76,9	69,6	
Press	Squeezing pressure [bar]	2	4	6	2	2	4	
	Press time [s]	85,7	81,1	80,7	78,5	80,9	79,1	
	Filtrate2 mass [g]	85,7	81,1	80,7	78,5	80,9	79,1	
Air dry	Air drying pressure [bar]	2	4	6	2	2	4	
	Dewatering time [s], T2	60	60	60	60	60	60	
Filtrate	Filtrate3 mass [g]	86,9	81,3	81,3	82,6	82,5	79,4	
	Filtrate clarity	ok	ok	ok	ok	ok	ok	
Cake	Tara 1 [g]	0,8	0,9	0,9	0,9	0,9	0,9	
	sample wet [g]	17,4	17,4	12,9	18,6	13,5	18,8	
	sample dry [g]	6,78	7,32	5,76	7,07	5,49	7,92	
	Cake thickness [mm]	14	15	9	14	10	13	
	Crack formation (*)	no	no	no	no	no	no	
	Shrinking (*)	no	yes	yes	yes	yes	yes	
	Remaining cake [%]	---	---	---	---	---	---	
	Cake texture (*)	wet	wet	wet	wet	wet	wet	
	Cake release	ok	ok	ok	ok	ok	ok	

Experimental results for Peat slurry

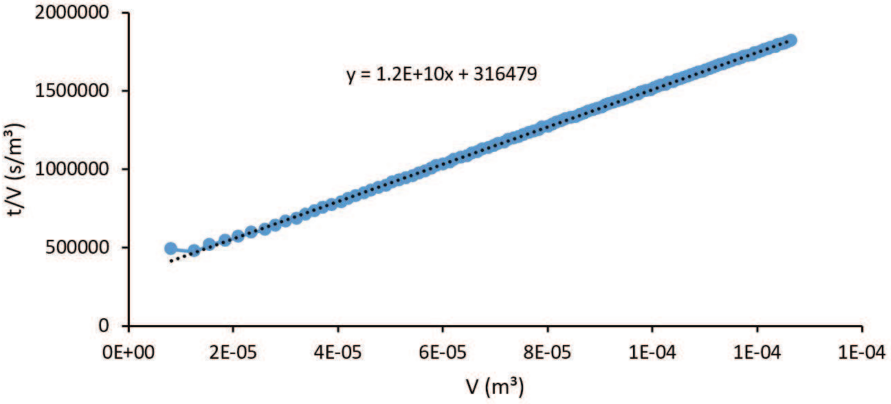
APPENDIX B. T/V PER V SLOPES



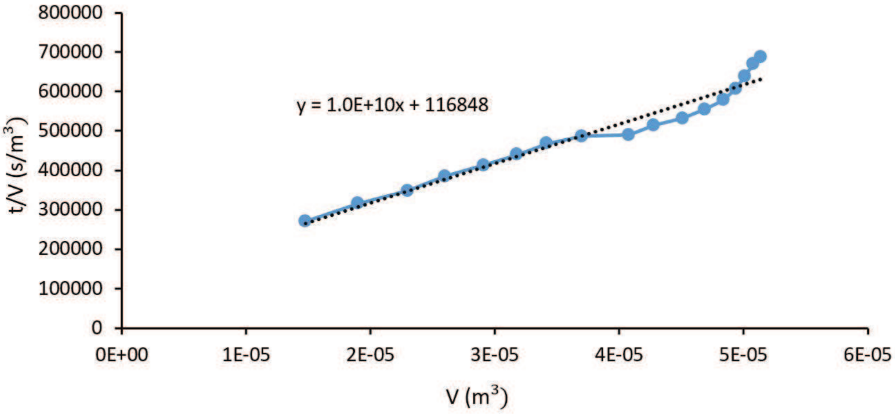
t/V per V for Peat 1



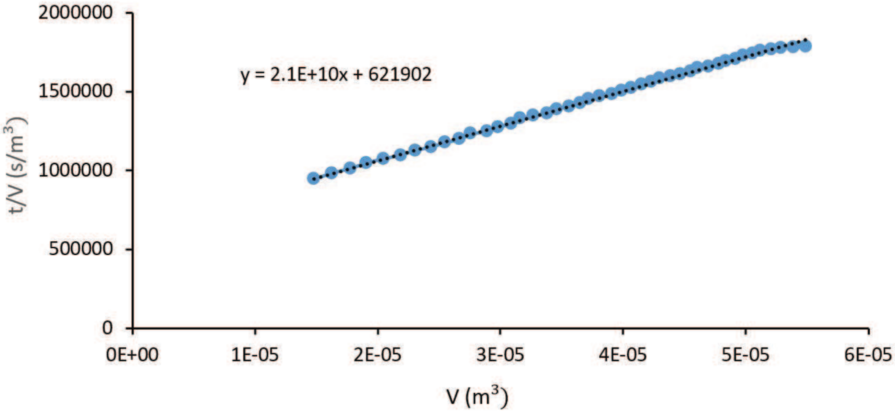
t/V per V for Lignin 1



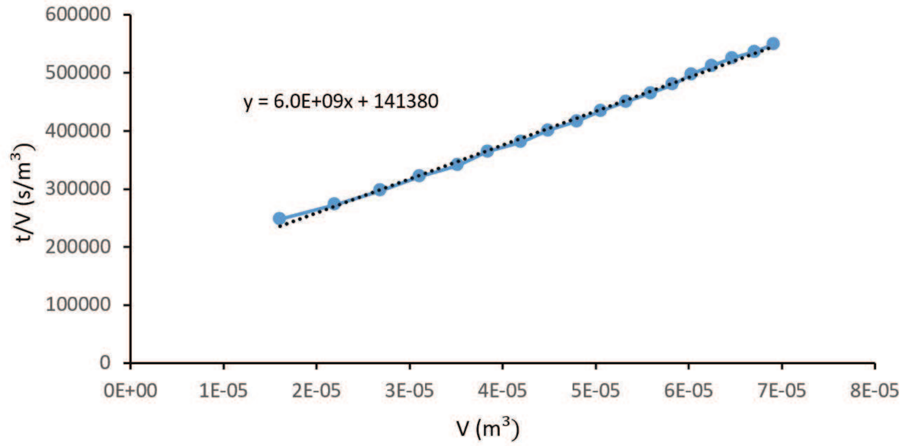
t/V per V for Lignin 2



t/V per V for Fibre 1



t/V per V for Fibre 2



t/V per V for Fibre 3