Evaluating Wood Fines as a Physical Conditioner for Dewatering Biosludge

By

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science, Graduate Department of Chemical Engineering and Applied Chemistry, in the University of Toronto

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Abstract

Wood fines are sometimes used to improve biosludge dewatering and to supplement primary sludge, but how they improve biosludge dewaterability is not well understood. Wood fines (0-78% moisture content, dosages of 50-300%), and primary sludge fibres are added to biosludge, dewatered with a Crown Press, and evaluated with a mass balance. The wood fines used absorb on average 2.8ml of water per gram dry weight, which is more water than they help release. Thus, the increase in the dry solid content of the filter cake is primarily due the dry mass of the wood fines themselves, not an increase in water removal. Primary sludge fibres outperformed wood fines when evaluated on the Crown Press without a polymer, but the two conditioners performed similarly when a polymer was used. In a field study, wood fines are found to be an unsuitable physical conditioner when tested in a laboratory scale screw press.
Acknowledgements

“A goal without a plan is a dream.  
A plan without commitment is hope”  
– Unknown author

I do not know where I found this quote. I only know that I read it just before I applied for my MASc at the University of Toronto, and thought how true and accurately it described my last seven years. The submission of this thesis completes a few goals I made shortly after the completion of my undergraduate degree. The rough plan was to obtain 5-7 years of practical experience, my P.Eng, and a MASc by my early thirties. Today, there is not much that can be accomplished individually, so I would like to thank the following people for helping me carry out the plan I made seven years ago, and helping me achieve all of my goals.

First, I would like to thank Professor James Wallace, whom I met shortly after my undergraduate graduation in 2008. He encouraged me to only pursue a MASc if I knew I wanted to research, and not for the degree. It was this advice that made me decide to work first and then return to school if the idea of conducting research still appealed to me. This proved to be one of the best decisions I have ever made. Next, my supervisors during my five years in the private sector: Chris Piche, Edward Humphries, Raul Domínguez, and Tony Dingman. They gave me the freedom to largely lead my own design projects, which allowed me to develop professional skills sooner than I hoped. My MASc supervisors, Professor Grant Allen and Professor Honghi Tran, for teaching me foundational research skills: maintain a healthy skepticism, only state what the data tells you, and, most important, the value of good writing and presentation skills. Lastly, I would like to thank my wife, Angela, for all her support over the last seven years. It wasn’t easy to leave a very promising career path to start out completely new again, but she supported my decision with the only stipulation that I knew it was what I wanted to do.

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1 Introduction

Along with cities and major municipalities, pulp and paper mills are required by law to treat their effluent prior to discharging it into a body of water. A common treatment process that can effectively remove the major contaminants is the activated sludge process. This process uses a mixed community of microorganisms to biologically degrade the effluent’s contaminants. Although this process is robust and effective, a disadvantage is the microorganism community grows and multiplies quickly. For stable and continuous operation, the mass of the microorganism community, the activated sludge, must be maintained at a specific target level. This is accomplished by continuously sending a portion of the activated sludge to waste. The activated sludge that is wasted is appropriately named waste activated sludge, or biosludge.

Canadian pulp and paper mills produce an average of 17 oven dry tonnes of biosludge per day (odt/d) (range: 1-60 odt/d) [1], and spend about 50% of the operational cost of the water treatment plant to treat and dispose of it [2]. Disposing of the biosludge is usually accomplished through a combination of landfiling, land application, or incineration. To lower disposal costs, it is desirable to remove as much water as possible, which reduces the volume and mass of biosludge to be handled.

In addition to biosludge, pulp and paper mills also produce primary sludge. Primary sludge, in the context of this thesis, is the fibres and fines that are lost from the pulping process and settle at the bottom of the primary clarifier. Primary sludge has a higher solids concentration than biosludge, and it dewateres better. Biosludge and primary sludge streams are usually mixed because the mixture is more dewaterable than biosludge alone. Mixing of the separate sludge streams also reduces the complexity of the dewatering plant operations. Despite this being a widely used practice, Amin reports in his MASc thesis that there is little literature on how primary sludge improves the dewatering of biosludge [3].

When there is a shortage of primary sludge, or an excess of biosludge, another operational practice at pulp and paper mills is to add wood fines. Wood fines, Figure 1, are a waste product from the mill’s chipping operations and are normally incinerated in the biomass boiler. It is highly desirable to incinerate dewatered biosludge within the biomass boiler to minimize disposal costs, so mixing wood fines with biosludge to improve the dewatering characteristics
and then incinerating this dewatered mixture is seen as an elegant solution of two waste streams. Any solid fuel that is burnt in the biomass boiler should have a low moisture content to avoid co-firing fossil fuels. In a survey of pulp and paper biomass boiler operations, the boilers tended to be operated with a maximum feedstock moisture content of 55% (45% DS) [4]. This is the moisture content, or corresponding dry solids content, that is commonly cited as an operational target for dewatering plants with subsequent incineration.

Figure 1: A sample of the wood fines used for this study

Wood fines are classified as a type of physical conditioner in the literature. Physical conditioners are added to reduce the compressibility of the biosludge, increase the filtration rate, and increase the dry solid content of the filter cake. Other than the filter press, there is a lack of literature that evaluates filter aids using lab scale apparatus that can simulate industrial equipment. This is important because the common laboratory test procedures used, such as the specific resistance to filtration and the capillary suction time, do not evaluate the entire dewatering procedure, namely the expression stage.

A couple of researchers have reported that adding wood products increases the dry solids content of the filter cake, but also reported that less filtrate is collected [5, 6]. This decrease in filtrate has not been thoroughly investigated, nor considered together with the dry solids content to determine if wood fines are a net benefit or detriment to the dewatering process. Therefore, it is intended to assess wood fines by dewatering mixtures of biosludge and wood
fines and to perform a mass balance to account for all of the water. Also, wood fines are stored outside and exposed to various weather conditions, which results in a variable moisture content. The effect of the moisture content on the wood fines ability to perform as a physical conditioner is unknown.

Since wood fines are being used as a substitute for primary fibres, we should know how well these materials perform relative to one another. This has not yet been studied. Also, being able to observe the interactions of the wood fines and the biosludge particles, and how the water moves through the mixture while being dewatered would also increase our understanding and provide insight into optimization strategies.

1.1 Objectives

The objectives of this thesis are as follows:

1) Evaluate if wood fines are a good physical conditioner to use for dewatering biosludge.
2) Determine if the moisture content of the wood fines is an important parameter to control.
3) Compare the performance of wood fines and primary sludge fibres to determine if wood fines are a suitable replacement material.
4) Make direct observations of the compressibility of biosludge.

This thesis begins with a brief overview of sludge and filtration theory. The reader is presented as to why applying pressure is important during dewatering. Next, how physical conditioners have been shown to reduce compressibility is reviewed as well as the recent findings and limitations of using wood based physical conditioners. The experimental methods used are then presented, and the Crown Press, the main evaluation tool used in this work, is introduced. The compressibility observations are presented first followed by the evaluation of the two physical conditioners: wood fines and primary sludge fibres. This thesis ends with a small set of experiments that use a lab scale screw press at a pulp and paper mill, and the implications that these results could have for industry.
2 Background

2.1 Biosludge and Primary Sludge

Biosludge is a dilute suspension of microorganisms, extracellular polymeric substances, inert particles, and water that is either not associated with the particles, or physically and chemically bound to them, Figure 2 [7]. The suspension can be 98-99% water and it behaves like a colloidal suspension. The density of biosludge is similar to that of water, so separation by gravity settling or centrifugation is difficult. Also, biosludge contains a high fraction of supracolloidal solids (1 to 100μm) [8], so separation by filtration requires a fine filter media to achieve high capture rates, but will quickly foul.

![Figure 2: Model of floc structure (reprinted with permission)\(^1\)](image)

Biosludge is also a highly compressible material. A compressible material is characterized by a proportional increase in the resistance to flow with an increase in applied pressure: increasing the filtration pressure does not increase the filtration rate [9] [10] [11]. The proportional increase in resistance is due to the formation of a layer called the filter skin near the filter medium. The pressure that this skin will form at, the critical pressure, has been determined to be as low as 2 kPa [9], and is much lower than the pressures typically used in industrial processes.

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\(^1\) Reprinted from Biomass & Bioenergy, 58, D. Mowla, H.N. Tran, D. Grant Allen, A review of the properties of biosludge and its relevance to enhanced dewatering processes, Pages 14., Copyright (2013), with permission from Elsevier.
dewatering equipment. Biosludge’s density, supracolloidal solids, and compressibility all contribute to biosludge having slower dewatering rates and lower absolute amounts of moisture removal than primary sludges.

Mixing biosludge with primary sludge before it is dewatered has been shown to result in higher dry solids contents (DS) than just biosludge alone [3, 6, 13]. It is usually mixed in high ratios: In a survey of Canadian pulp and paper mills, a mixture of 63% primary: 37% biosludge is reported [1]. It is known that when this ratio decreases the dewaterability of the mixtures is reduced, but the reduction in dewaterability is not necessarily linear. Mäkinen et al. [13] found that they could reduce the fibre content of a pulp and paper sludge down to 13% before they saw a significant change in the dewaterability.

Amin [3] mixed various ratios of primary sludge and biosludge, with and without polymer, and evaluated the dewaterability on a Crown Press. Adding primary sludge to biosludge up to 40% (solids mass content of the slurry) without polymer linearly increased the DS of the filter cake. At a mixing ratio of 40%, the DS of the filter cake was twice the DS of a biosludge filter cake with no primary sludge added. When polymer was used, a mixture consisting of just 20% primary sludge (solids mass content of the slurry) obtained a filter cake DS two times greater than a filter cake made from a mixture of just biosludge and polymer. These results, however, were not obtained with each of the three primary sludges that were tested. Amin concludes that the nature of the solid particles is a factor in how primary sludge improves biosludge’s dewaterability.

Kyllönen et al. [14] studied the components within pulp and paper biosludge and found that particles greater than 75um correlated well with a higher DS of the filter cake as well as increasing the rate of filtration. Amin [3] measured the particle sizes of the sludge mixtures and found that adding primary sludge increased the amount of particles in the settleable particle size range (>100um), a size range favorable to improving dewaterability. He was unable to determine if the increase in size was due to agglomeration, or if the particles were contributing to the filter aid effect by creating larger, more robust particles.

Together, primary sludge and biosludge represent a considerable volume of waste from a pulp and paper wastewater treatment plant. In order to reduce the volume and mass of the sludge to
be disposed, wastewater plants employ some combination of machinery to thicken and dewater the sludge. When selecting which type of equipment to use, the plant must consider factors such as familiarity with operating the equipment, local service expertise, maintenance requirements, and specific characteristics of the sludge to be processed.

2.2 Industrial Dewatering

For the first step in dewatering, the mixture of sludge is usually thickened, with the gravity belt table being one method. Next, vacuum filters, centrifuges, belt filter presses, screw presses, or filter presses can be used to further dewater the sludge. Table 1 presents typical equipment, operation pressures, and performance in terms of DS for municipal sludge. A detailed description of the equipment operation and design can be found in the EPA design manual [15]. Comparable performance data for pulp and paper sludges, when data was available, is indicated by references [1, 13].

Table 1: Operating pressures and performance in terms of %DS of typical dewatering equipment in municipal wastewater treatment and pulp and paper wastewater treatment plants. Screw presses are operated to be within a target range of the rated full load amps: no pressure reading is available.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity Belt Table</td>
<td>Atmospheric</td>
<td>4-8%</td>
<td>13-16%</td>
<td>Data not available</td>
</tr>
<tr>
<td>Vacuum Filter</td>
<td>34 kPa vacuum</td>
<td>12-18%</td>
<td>26-33%</td>
<td>18-25%</td>
</tr>
<tr>
<td>Solid Bowl Centrifuge</td>
<td>600-3000G</td>
<td>15-20%</td>
<td>28-34%</td>
<td>12-30%</td>
</tr>
<tr>
<td>Screw Press</td>
<td>Not applicable</td>
<td>11-17%</td>
<td>41% [1]</td>
<td>31% [1]</td>
</tr>
<tr>
<td>Filter Press</td>
<td>690-1380 kPa</td>
<td>27-34%</td>
<td>40-46%</td>
<td>Data not available</td>
</tr>
</tbody>
</table>

Excluding the centrifuge, two trends can be observed in the table. First, there is an increase in DS as the applied pressure is increased. Second, primary sludges dewater more completely than biosludges, and mixtures of the two fall in between depending on the specific mix ratio of primary sludge to biosludge. The filter press can typically achieve the highest DS, but it is not used in large scale plants because it processes sludge slower than the centrifuge, belt filter press, and screw press.
Belt filter presses can dewater pulp and paper primary sludge to 35% DS. However, a belt filter press can dewater pulp and paper biosludge to only 13-16% DS [12]. This is still considered a wet cake because the minimum DS for disposal at a landfill can be as high as 25% DS [17]. The belt filter press is of particular relevance to this thesis and will be discussed in greater detail.

2.2.1 Belt Filter Press

The belt filter press generally consists of two tensioned belts that are passed between a series of rollers. The belts are commonly both water permeable, but designs exist where only one belt is. The rollers vary in diameter with smaller diameter rollers exerting more pressure than larger diameter rollers for a given belt tension. By varying the diameter of the rollers, belt filter press designers can control the pressure exerted on the sludge as it travels through the machine.

The belt filter press is generally divided into different pressure zones. These zones are: the gravity (or free) drainage zone, the low pressure zone, and the high pressure zone (Figure 3). The gravity drainage zone allows the majority of the free water to drain from the sludge after polymer conditioning, and is necessary to prevent sludge from squeezing out of the belts in the remainder of the belt filter press. This zone increases DS from 1-2% up to 6-12%. In the low pressure zone, the upper and lower belts come together to form a wedge shape. Residual water left over from the gravity drainage zone is forced out and the sludge cake is formed in preparation for the high pressure zones. In the high pressure zone, the sludge is passed over rollers of decreasing diameter to apply increasingly higher pressure to squeeze out as much water as possible. The belts in this zone also travel at slightly different speeds as they move around the rollers to produce a slight shearing action, which helps to release water that is trapped within the sludge. After the sludge is released from the belts, the belts are washed with high pressure spray nozzles, and the cycle is repeated.
2.3 Specific Resistance to Filtration

To study the filtration characteristics of biological sludges, the specific resistance to filtration test is often used. The parameter of interest, the specific resistance to filtration (SRF), is a measure of how much the sludge solids in the filter cake resist the movement of filtrate through the filter cake. The theoretical basis for the filtration model was originally developed by Carman for incompressible substances [18]. Gale [19] summarizes how researchers have demonstrated how the filtration theory developed for incompressible cakes also applies to compressible cakes. The equation that is used today by researchers to calculate SRF is:

---

\[ \frac{\theta}{V} = \frac{\eta \bar{r}^* C^*}{2P_T A^2 V} \]  

(1)  

Where:  
\( \theta \) = time [s];  
\( V \) = filtrate volume [m³];  
\( A \) = filtration area [m²];  
\( \eta \) = viscosity of filtrate [kg s⁻¹ m⁻¹];  
\( \bar{r}^* \) = mean specific resistance to filtration [m kg⁻¹];  
\( C^* \) = mass of dry solids deposited per unit volume of filtrate [kg m⁻³];  
\( P_T \) = Total pressure drop across the filter media and cake [kg m s⁻²].

The SRF is determined by plotting \( \theta/V \) against \( V \), and then measuring the slope of the line. The parameters \( P_T, A^2, \eta, C^* \) are known experimental values or can be measured, and are assumed to be constant during the experiment. Rearranging the above equation and inserting the measured slope produces the SRF.

\[ \bar{r}^* = \frac{2P_T A^2}{\eta C^*} b \]  

(2)  

Where:  
\( b \) = slope of the time/volume versus volume plot [s m⁻⁶].

A high specific resistance means a low filtrate volume per unit of dewatered sludge. Raw biosludge typically has a SRF of 1-10x10¹³ [m kg⁻¹], and properly conditioned biosludge typically has a SRF of 2x10¹¹ [m kg⁻¹], a two orders of magnitude improvement [20].

One of the reasons why conditioning biosludge can reduce the SRF is how the particles in the biosludge are altered. Gale describes how the SRF relates to the structure of the filter cake using the Kozeny equation [19]. The Kozeny equation, shown below, is presented in a form which relates the particle specific surface area, \( S_o \), and void fraction, \( \epsilon \), to the SRF.

\[ \bar{r}^* = K S_o \frac{2(1 - \epsilon)}{\epsilon^3} \frac{1}{\rho_p} \]  

(3)  

Where:  
\( K \) = Kozeny constant;  
\( S_o \) = Surface area of a unit volume of particles [m⁻¹];  
\( \epsilon \) = Void fraction;  
\( \rho_p \) = Particle density [kg m⁻³].

Conditioning biosludge usually involves adding a cationic polymer. The cationic polymer neutralizes the negatively charged particles of the biosludge and promotes the agglomeration of
the individual particles into larger flocs. As the volume of the particles increases, the specific surface area, and the \( S_0 \) term, is reduced. Since there is less surface area, there are less frictional forces acting on the filtrate as it flows through the filter cake, which reduces the SRF.

Focusing now on the void fraction, \( \epsilon \), small decreases in this parameter can cause large increases in the SRF [19]. Figure 4 is plotted with the voidage term on the y-axis in logarithmic scale, and the void fraction term on the x-axis. A decrease in void fraction from 0.4 to 0.2 would cause a tenfold increase in SRF. The increase in SRF is caused by an increase in the frictional forces exerted on the fluid particles as they pass through the smaller channels.

![Figure 4: Effect of filter cake void fraction on the specific resistance to filtration [19]](image)

Since biosludge is a compressible material, increasing the pressure during filtration will cause the particles to deform, which decreases the void ratio and causes an increase in SRF. This decreases the rate at which filtrate is removed from biosludge, an important operational parameter. Dewatering at lower pressure, i.e. atmospheric pressure, can minimize this problem, but for industrial scale operations higher pressures are necessary.
2.4 The Importance of Applying Pressure

The DS of the filter cake is desired to be as high as possible because this minimizes the volume to be disposed, and it improves the combustibility of the filter cake. It is only when higher pressures are applied that a high DS is achieved. For this reason, Novak et al. argued that the expression stage of dewatering may be more important than the filtration stage [21].

The filtration stage is characterized by the presence of a filterable slurry above the filter cake, and the increasing height of the filter cake ($\Delta L$ increases), Figure 5. Once the slurry is exhausted and the piston touches the top of the filter cake, the expression stage has commenced. During expression the height of the filter cake is decreasing ($\Delta L$ decreases), and the porosity of the filter cake is reduced. The more compressible a material is, the more the height of the filter cake will be reduced during the expression stage.

![Figure 5: Schematic of the filtration and expression stages of dewatering.](image)

The operational performance of a gravity filter belt (a filtration stage device) and a belt filter press (an expression stage device) for dewatering biosludge are shown in Figure 6. The relationship in Figure 6 is calculated by assuming a volume of sludge with a solids content of 1.5%. Then, as water is theoretically removed the DS of the sludge is recalculated at multiple points as per the following equation.
Gravity filter belts can remove 75-85% of the original water content in the sludge and achieve a typical DS of 4-8% [15]. The belt filter press, located immediately downstream of the gravity filter belt, will press the sludge and remove between 5-10% of the original water content. Despite the expression stage removing less water relative to the filtration stage, the DS of the filter cake is doubled to 13-19% [15].

Applying higher pressures will remove even more water, and result in a higher DS, but these higher pressures need to be applied over a longer period of time. This is because higher pressures will compress the filter cake more and further reduce the void fraction within the cake. Having a smaller void fraction means there is a larger resistance to the movement of water within the filter cake, so the rate of filtration is reduced. Dewatering sludge at higher pressures to get a high DS while maintaining an acceptable rate of filtration is the optimization challenge for researchers and engineers. The strategy is to add conditioners to the sludge to make it less compressible when higher pressures are applied.
3 Literature Review

3.1 Visualizing Compressibility

The attempts to observe the filtration of compressible slurries, and in particular biosludge, are concerned with validating and improving theoretical models of compressible filter cakes. Physical conditioners can be added to biosludge in an attempt to reduce the compressibility and maintain porosity. Figure 7 shows a schematic of what is believed to occur within biosludge, but this process is very difficult to observe.

Figure 7: Schematic representation of a physical conditioner acting as a skeleton builder within a compressible filter cake (reprinted with permission)³

There have been a few of studies where the filter cakes of compressible materials have been sectioned and the porosity of the filter cakes observed. Hwang et al.[22] micro-filtered Dextran MnO₂ particles to simulate a soft colloid and found there were three distinct stages of cake growth. They cross-sectioned the filter cake during the second stage of cake growth, characterized by a rapid increase in SRF, and observed a thin, very tightly packed layer of particles adjacent to the filter media. This they took as evidence of the formation of a filter skin. Thapa et al. [23] mixed lignite with anaerobic sludge and viewed the wet and dry filter cakes with an environmental scanning electron microscope (ESEM) and scanning electron

³ Reprinted from P. Amin, Primary sludge addition for enhanced biosludge dewatering, Pages 107., Copyright (2014), with permission from P. Amin
microscope (SEM) respectively. They found that the sludge surrounded the lignite particles, which provided structural support and maintained the porosity of the filter cake. Using an SEM, Nittami et al. [24] found that viscose rayon and polyethylene terephthalate fibres created larger void spaces in the filter cake than polypropylene fibres or the control case (no added fibres), and attributed this to the higher DS in the former mixtures.

One of the first direct observations of a filter cake forming was performed by Chase et al. [25] with a dilute solution of Solka Flocs® (cellulose fibres). They observed the buildup of individual fibres and the subsequent collapse of the filter cake which they attributed to an increase in flow through the filter cake. Using Nuclear Magnetic Resonance imaging, Heij et al. [26] plotted the porosity profiles of ferric chloride and lime conditioned biosludge during both the filtration and expression stages. During the filtration stage there is a porosity gradient that increases from the filter media to the slurry-filter cake interface. Once expression starts, the gradient is gradually reduced towards a more constant porosity profile across the entire filter cake.

There is a lack of direct observation of filter cake formation of compressible materials in general, and biosludge in particular. A portion of the work contained in this thesis is concerned with trying to visualize the filtration of the biosludge with an added physical conditioner.

### 3.2 Conditioning Biosludge to Reduce Compressibility

Biosludge has been conditioned with inorganic chemicals as well as with physical conditioners such as coal, lime, fly ash, char, wood, and agricultural by-products to reduce its compressibility [5, 22, 24, 28]. This thesis focuses on physical conditioners, which are also known as skeleton builders, for the structural rigidity they provide, or as filter aids because of their tendency to speed filtration during dewatering and improve cake handling properties. Physical conditioners often do not perform well without a chemical conditioner to destabilize the colloidal biosludge. In a recent review of filter aids used for dewatering, Qi et al. highlighted a trend that lower amounts of physical conditioners could be used if mixed with a polymer [28].

One of the earlier studies on the use of physical conditioners to reduce the compressibility of sludges was performed by Zall et al. [27]. They treated an oily sludge with polymer, hydrated
lime, and fly ash and measured the degree of compressibility of each treatment using the empirical equation:

\[ r = r' p^s \]  (5)

Where:
- \( r \) = specific resistance to filtration \([m \, kg^{-1}]\);
- \( r' \) = specific resistance to filtration at reference pressure \([m \, kg^{-1}]\);
- \( P \) = ratio of applied pressure to reference pressure;
- \( s \) = compressibility coefficient.

An incompressible filter cake, such as a gravel bed, would have a compressibility coefficient close to zero, whereas a compressible cake would have a compressibility coefficient of one or greater. The raw sludge sample and the polymer treated sample both exhibited a similar degree of compressibility \((s = 1.5)\), but the hydrated lime and fly ash treated samples were markedly reduced \((s = 0.35\) and \(0.17\) respectively). Not only was the compressibility reduced, but the time to reach the end of primary consolidation was also greatly decreased. The fly ash and lime samples finished in 10 and 15 minutes respectively. The polymer treated sample had not yet reach the same degree of consolidation after 35 hours.

Novak et al. [21] investigated the dewaterability of biosludge using a polymer as well as inorganic conditioners: ferric chloride plus lime. They found that both conditioning methods raised the critical pressure of the sludge, the pressure at which the filter skin forms, but neither raised it to the pressures typically encountered in an industrial belt press. Similar to Zall et al.’s findings, Novak et al. were able to show that ferric chloride plus lime greatly increased the rate of filtration during high pressure filtration, and that polymer conditioned sludges can attain the same level of dryness if sufficient time is allowed to elapse. The ferric chloride plus lime conditioned biosludge achieved the peak dryness in 22 minutes of pressure filtration compared to 22 hours for the polymer conditioned biosludge. Novak et al. [21] proposed that the ferric chloride plus lime provided a rigid structure within the biosludge, which maintained the porosity so that the biosludge could be dewatered at a faster rate. Work by Deneux-Mustin et al. [29] supports this hypothesis. They observed that the iron plus lime conditioner formed precipitates on the outside of the floc, which could transmit applied mechanical stress.

Smollen and Kafaar [30] conditioned biosludge with a polymer and char, and then dewatered the sample using a laboratory filter press. The resulting DS of 40% was attributed to the
combination of the polymer making large flocs, and the char particles for adding rigidity to resist compression. Thapa et al. [23] mixed anaerobically digested sludge with lignite coal and concluded that the increase in DS was a result of reducing the compressibility of the sludge. They measured the porosity of the sludge cakes and found that the lignite helped to maintain the porosity of the sludge; thus, this allowed for a faster drainage.

While polymer conditioned biosludge and physical conditioned biosludge will ultimately attain the same level of dryness, using physical conditioners will enable the maximum level of dryness to be reached in less time. Adding organic physical conditioners to improve dewatering has an additional benefit of increasing the caloric value of the sludge. This is particularly attractive if incineration is the final means of sludge disposal. Due to their availability and the possible benefit they would provide to biosludge combustion, various wood products have also been studied for their potential as physical conditioners.

### 3.3 Using Wood Products as Physical Conditioners

When physical conditioners are discussed in the literature, the amount that is added to biosludge is presented as a percentage of the dry solids of the biosludge. For example, if the DS of the biosludge is 15g/l, and a wood fine dosage of 200% is added, that would mean 30g of wood fines per litre of biosludge is being added. This notation will be used in the remainder of this thesis to note the various dosages of wood fines, or other physical conditioners, that were used in the studies.

Wood products have been shown to decrease the compressibility of biosludge during filtering, but there are difficulties in properly assessing their overall benefit as well as determining their optimum dosage. Because dry solids are added to the biosludge the most important and basic performance metric, the DS of the filter cake, is difficult to interpret. The effectiveness of traditional laboratory equipment to assess improvements in dewaterability is also suspect. Finally, it is known that the wood particles absorb water to some degree, but how much is unknown.

#### 3.3.1 Impact on Dry Solid Content Measurements and Optimum Dosage

The DS of the filter cake when adding a physical conditioner such as wood fines is calculated using the following equation, where all values are calculated on a mass basis:
Adding physical conditioners in the large amounts typically needed can directly affect the dry solid measurement in three ways. First, more biosludge solids can be captured. Second, adding wood fines increases the DS simply because dry mass is being added to the system. Third, water can be removed from the system. In order to definitively state that wood fines are improving the DS, it must be proven that more biosludge solids are being captured, or more water is being removed, or both. This is different from using a polymer, which adds an almost negligible amount of mass to the slurry, so the increase in the DS can confidently be attributed to the polymer capturing more biosludge solids and removing more water.

Specifically for wood based physical conditioners, the optimum amount reported in the literature varies (Table 2). Not only is the type of sludge used in the evaluations different, but the test methods and the type of physical conditioner also varies. In the case of refined bark, the 300% dosage of physical conditioner used is not unusual. Fly ash, for example, has been recommended to be added at dosages as high as 500% [28, 32]. Also, the studies in Table 2 did not adequately account for how the DS increased. Not surprisingly, it is difficult to make a recommendation to industry on the appropriate amount of wood fines to use.

<table>
<thead>
<tr>
<th>Filter aid</th>
<th>Sludge Type</th>
<th>Optimum Dosage [g/g biosludge]</th>
<th>Investigator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hog fuel Sawdust</td>
<td>Deinking biosludge</td>
<td>40%</td>
<td>Zhao H. [6]</td>
</tr>
<tr>
<td>Sawdust</td>
<td>Deinking biosludge</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>Sawdust</td>
<td>Textile biosludge</td>
<td>60%</td>
<td>Luo et al. [32]</td>
</tr>
<tr>
<td>Wood chips</td>
<td>Municipal biosludge</td>
<td>90%</td>
<td>Lin et al. [5]</td>
</tr>
<tr>
<td>Wood chips</td>
<td>Municipal biosludge</td>
<td>100%</td>
<td>Ding et al. [33]</td>
</tr>
<tr>
<td>Shredded Bark</td>
<td>Kraft biosludge</td>
<td>300%</td>
<td>Marshal et al. [34]</td>
</tr>
</tbody>
</table>

Accounting for the effect that physical conditioners have on the calculated DS is not consistent in the literature. Zhao [6] as well as Ding et al. [33] report the DS with no mention of the proportions of physical conditioner and biosludge solids in the filter cake. Sometimes researchers report a total DS and a net DS, which is the amount of filter aids subtracted from the total solids [31, 34]. The implicit assumption is that everything is homogenous and any losses were equal between the physical conditioner and the biosludge during the experiment.
Vesilind [35] argues that assessments of physical conditioners can only be done by conducting a mass balance.

When assessing chemical conditioners, tests such as the capillary suction time (CST), Figure 8, and the SRF will exhibit a clear minima when the optimal dosage is used. Physical conditioners do not show this same response. Instead, they will continue to show improvements until the performance of the pure filter aid is reached. Thapa et al. [23] demonstrated this when they tested various doses of lignite in anaerobically digested sludge using the SRF test. The SRF continually decreased until it approached pure lignite, and did not exhibit any optimum value.

![Typical CST response to an increasing dosage of a cationic polymer being added to a sludge](image)

Figure 8: Typical CST response to an increasing dosage of a cationic polymer being added to a sludge (reprinted with permission)

More recently, researchers have been using the net yield equation to evaluate physical conditioners [5, 28, 33, 38, 39]. Rebhun et al. [38] introduced the net yield equation to address the inability of the SRF test to predict an optimum dosage when physical conditioners are used.

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4 Reprinted from Water Pollution Control Federation, P. A. Vesilind, Capillary suction time as a fundamental measure of sludge dewaterability, Pages 5. Available at : http://www.jstor.org/stable/25043483
The yield of a filtration process is the amount of sludge solids captured per unit filtration area per unit time:

\[ Y = \frac{C^*V}{\theta A} \]  

(7)  

Where:

- \( Y \) = yield [kg m\(^{-2}\) h\(^{-1}\)];
- \( C^* \) = mass of dry solids deposited per unit volume of filtrate [kg m\(^3\)];
- \( V \) = filtrate volume [m\(^3\)];
- \( \theta \) = time [h];
- \( A \) = filtration area [m\(^2\)].

And the yield can be related mathematically to the SRF [38].

\[ Y = \left( \frac{2P_T C^*}{\eta \bar{r}^* \theta} \right)^{0.5} \]  

(8)  

Where:

- \( P_T \) = Total pressure drop across the filter media and cake [kg m s\(^{-2}\)];
- \( \eta \) = viscosity of filtrate [kg s\(^{-1}\) m\(^{-1}\)];
- \( \bar{r}^* \) = mean specific resistance to filtration [m kg\(^{-1}\)].

However, the yield represents the total amount of solids present in the slurry, which a significant proportion can be attributed to the added physical conditioner. Since the increase in the capture of the biosludge particles is of primary importance, Rebhun et al. [38] applied a correction factor, \( F \), to arrive at the net yield equation.

\[ Y_N = F \left( \frac{2P_T C^*}{\eta \bar{r}^* \theta} \right)^{0.5} \]  

(9)  

Where:

\[ F = \frac{\text{biosludge dry solids}}{\text{biosludge dry solids} + \text{conditioner dry solids}} \]

When adding a physical conditioner the SRF term continuously decreases and the yield continuously increases (Figure 9). By adding the correction factor, there comes a point when the decreasing fraction of biosludge solids in the slurry (caused by adding physical conditioner) outweighs the decrease in SRF and causes the yield to go through a maxima.
Although the net yield equation indicates an optimum dosage of physical conditioners, it is suspected that this is not the point of maximum dewaterability. This is because of how the two dominant terms in the yield equation, the SRF and C*, are calculated, and what they physically mean. As mentioned above, and shown in Figure 9, adding physical conditioners to a sludge tends to decrease the SRF to a lower constant value. This is because the physical conditioner eventually is added in large enough quantities to become the dominant constituent of the slurry, and the slurry’s characteristics are then determined by the physical conditioner. Since physical conditioners tend to be incompressible, the SRF assumes a constant value. With the SRF term no longer decreasing, the changes to the increases in the yield start to become smaller. However, the correction factor continues to decrease because the amount of sludge solids is

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5 Reprinted from Water Pollution Control Federation, M. Rebhun, J. Zall, N. Galil, Net sludge solids yield as an expression of filterability for conditioner optimization, Pages 3. Available at: http://www.jstor.org/stable/25046886
constant, and the amount of physical conditioners, within the denominator of the correction factor, continues to increase. At the same point as where the SRF stops changing, the correction factor becomes the dominant term and starts decreasing the yield.

The $C^*$ term, dry mass of solids per volume of filtrate, also causes the yield to increase. This is because the volume tested is always finite, but adding physical conditioners will always increase the dry mass of the filter cake. Additionally, if the physical conditioners can absorb large quantities of water, this will cause a decrease in the amount of filtrate to be collected, which will artificially raise the $C^*$ term. Similar to the effect that physical conditioners have on the SRF, the added DS of the filter cake will eventually plateau at the DS of the added physical conditioners. Once it does plateau, the yield will start to decrease driven by the correction factor, which will continue to become smaller as more physical conditioners are added.

Therefore, it is suspected that the optimum point in the net yield equation indicates the point where the slurry properties have changed to be controlled by the physical conditioner rather than the biosludge solids. For this reason a mass balance will be used instead to determine how different dosages of physical conditioner changes the biosludge dewatering properties.

### 3.3.2 Decrease in Volume of Filtrate Collected

Moisture absorption by wood based physical conditioners is a problem that has been mentioned by almost all of the investigators working with them. Marshal et al. [34] noted that the dry solids content increased linearly with the amount of bark added, and would likely approach a maximum equal to the affinity for water that the shredded bark would have. As part of her thesis, Zhao [6] measured the DS of the sawdust and hog fuel before and after pressing in the laboratory press and found a change from 95% to 28%DS for sawdust and 73% to 35%DS for hog fuel.

Lin et al. [5] used the time to filter (TTF) test to assess the dewaterability of wood chips. They noticed that with higher levels of wood chips the TTF decreased and the DS of the filter cake increased, but the total volume of filtrate did not consistently increase. In some cases, less filtrate was actually recovered. Collecting less filtrate would suggest a decrease in dewaterability. It is important to understand if the wood fines help to release more water than they absorb, and produce a net benefit to biosludge dewaterability.
3.3.3 Conventional Dewaterability Assessment Tools

Common tools used in the literature to assess dewaterability of sludges include the SRF, CST, and TTF. They are popular because they are easy to perform with standard laboratory equipment, and provide some insight into the dewatering characteristics of the sludge. However, they do have their shortcomings and specific problems when evaluating physical conditioners.

The SRF test is most commonly performed using a Buchner funnel to filter a small sample of sludge, approximately 100-300ml, under a vacuum of 50kPa [20]. This pressure is below the pressures normally used in the expression phase of dewatering equipment. Additionally, the sample sized typically used produces biosludge cakes that are thinner than those produced on industrial equipment. Novak et al. [21] found that when thin cakes are produced there is little difference in filtration time between polymer or ferric chloride plus lime. However, when thick cakes were studied the ferric chloride plus lime conditioned biosludge filtered faster. Exclusively using SRF to assess biosludge conditioning will favor polymers because of the thin cakes typically produced, instead of the conditioning agent that works best for the thickness of cake actually produced on the dewatering equipment.

Using the CST to evaluate physical conditioners also has its problems. The small sample size required for the test, typically only 3-5ml, requires the sample to be homogeneous. This can be difficult to attain as wooden physical conditioners can have a large size distribution and large individual particle sizes (particles up to 4.75mm have been used [34], [39]). Additionally, CST is not well suited to make comparisons between sludges of different solids concentrations [40], and, like the SRF, it does not have sufficient compressive forces to assess the physical conditioners reduction of the filter cake compressibility.

The TTF test is a standardized test that involves filtering a known volume of sludge and recording the time it takes for 100ml of filtrate to collect. Once again, this test is limited to testing filterability and not expression. Additionally, if the filter aids can absorb water, the results may not be representative of the true improvement to dewaterability.

The above mentioned limitations have led researchers to use lab scale filter presses as well as compression cells to study physical conditioners[33], [41]. These apparatus do not impart a
shearing mechanism during mechanical dewatering, so they cannot be used to predict industrial scale dewatering results on belt filter presses nor screw presses.

For the above reasons, SRF, CST, and the TTF, are not well suited to assess physical conditioners. The common problem with the lab techniques is their inability to properly assess the expression phase. Using lab scale filter presses and compression cells is an improvement over the lab techniques, but they do not simulate belt filter presses nor screw presses, which are common dewatering devices found in pulp and paper mills. There is also a lack of literature concerning the performance of physical conditioners on belt filter presses [28], and a study that assessed wood based physical conditioners with a mass balance could not be found. For these reasons, a Crown Press will be used along with a mass balance to assess the improvement to biosludge dewaterability by physical conditioners.

3.3.4 The Crown Press Dewaterability Assessment Tool

The Crown Press is a laboratory device designed to simulate the operation of an industrial scale belt filter press, Figure 10. Graham [42] has shown that the Crown Press can be used to assess conditioning methods and predict how they will perform in industrial operation. The device generally consists of a gravity filter, a semi-circular crown, two pieces of filter belt fabric, and a means to apply linear tension on the belts and pull them over the crown. The applied pressure is measured by a pressure transducer, which is used to calculate how much force is being applied to the biosludge. Water is collected from both the gravity settling operation as well as the filter belt pressing operation to be used in further analysis.
Figure 10: The Crown Press dewaterability assessment tool

The device has been calibrated as part of a master’s thesis by Amin [3], and applies a maximum pressure of 112.4 kPa (16.3 psig) between the two filter belts. While this is on the low end of the operation pressure range of industrial pressures, it is three times higher than the pressures used by Graham [42] in his thesis work using the device to predict actual belt filter press operation.

3.4 Significance of Objectives

From a review of the literature, a few areas have been identified where there is a lack of knowledge and the objectives of this thesis would help fill. While there have been studies on wood based physical conditioners, it is not obvious if a mass balance was performed to determine how the dry solid content of the filter cake was increasing. Performing a mass balance would also elucidate why less filtrate is recovered and if wood based physical conditioners are a net-benefit to dewatering biosludge.

Studies could not be found that assess wood based physical conditioners on a belt filter press or a screw press. Moreover, a comparison as to how primary sludge fibres and wood fines perform relative to one another could not be found. Lastly, there are only a few studies that have attempted to observe the formation of compressible filter cakes, and none could be found that studied biosludge and wood fine mixtures.
4 Methods and Materials

Experimental materials are presented first, followed by a description of the equipment used. The dewatering test protocol, which encompasses the majority of the work in this thesis, is presented next. Lastly the methods and equipment used in the work performed as part of the field studies at a pulp and paper mill are stated.

4.1 Materials

4.1.1 Sludge

Sludge samples were collected and shipped from a pulp and paper mill on a bi-weekly basis. Samples were collected from the secondary clarifier and primary clarifier for the biosludge and primary sludges respectively. The primary sludge clarifier’s influent originates from a bleached chemi-thermo-mechanical pulping process. Sealed in 20L pails, the samples were shipped to the university laboratory, typically a 3 day shipping time. They were stored at 4°C upon receipt until ready for use.

Since the characteristics of the sludge can change from sample to sample, each individual experiment was conducted with sludge from a single 20L pail when possible. For each experiment, the required amount of sludge was decanted from the 20L pail and heated to 20°C with a warm water bath.

4.1.2 Wood Fines

A 1.125kg sample of wood fines used in these experiments was dried in an oven overnight at 103°C. A US 6, US 16, US 35, and US 70 mesh sieves (opening sizes of 3.36, 1.19, 0.5, and 0.21mm respectively) were chosen to sieve the sample and characterize it according to mass.

The as-received moisture content of the wood fines is approximately 10%.

4.1.3 Primary Sludge Fibres

Primary sludge fibres were obtained by filtering pulp and paper primary sludge through a US 100 sieve (opening size 0.149mm) and subsequently rinsed it with tap water. The fibres were then spread on aluminum foil and dried in an oven at 103°C overnight. The dried fibres were
then separated into small clumps with a mortar and pestle, and then quickly pulverized in a residential coffee grinder (3-5 seconds) to assist with their dispersion when they were added into the biosludge.

4.1.4 Polymer
A high cationic charge polymer, Zetag 8165 (BASF), was used for applicable experiments. A stock solution (250ml) was made with dry powder and mixed with distilled water to a consistency of 0.5 wt% (5g/l). The stock solution was mixed at least 24h prior to use and was kept for a maximum of seven days. The polymer dosage used is indicated within the results and discussion section for each particular experiment.

4.2 Measurement Methods and Apparatus

4.2.1 Total Solid Measurements
Total solid measurements of sludges and of water collected during dewatering were made according to Standard Methods 2540 B [43]. Each measurement was performed in duplicates.

Total solids of the filter cake was performed according to Standard Methods 2540 G [43]. The calculation to determine the total solids, which is also the DS of the filter cake, is shown below to illustrate the individual components. Each measured parameter is less the weight of the empty weighing dish. For every replication the entire filter cake was divided between two weighing dishes.

\[
DS = \frac{(Dry\ Biosludge + Dry\ Wood\ Fines)}{(Dry\ Biosludge + Dry\ Wood\ Fines + Water)} \times 100 \quad (10)
\]

All mass measurements were performed on an analytical balance (Denver Instruments Model: APX-100) capable of measuring 0.1mg.

4.2.2 Capillary Suction Time
A Type 304M Laboratory CST Meter and 7x9cm CST Paper (Triton Electronics Ltd.) was used to assess the CST of the biosludge. Tests were performed in triplicates, 3ml samples, 22°C ±2°C.
4.2.3 pH

pH measurements were made using a VWR sympHony Benchtop meter (VWR International).

4.2.4 Filtration Videos

Sludge filtration videos were filmed using a Canon ELPH 300HS camera and a glass filtration unit (Advantec vacuum glass filtration unit, Model: KG25, 15ml holder, stainless steel support, 100 mesh). One series of videos was made using only 20ml of biosludge plus polymer, dosed at 20kg/tonne DS. A second series of videos was made using 20ml of biosludge mixed with 0.7g of wood fines (200% dosage). The biosludge-wood fines mixture was allowed to rest for 10 minutes and then polymer was then added, dosed at 20kg/tonne DS. Both samples were mixed by lightly shaking the falcon tube. Vacuum pressure was 24kPa for 1 minute.

4.2.5 Crown Press

A laboratory Crown Press (Phipps & Bird Inc.) was used to evaluate the extent of dewaterability. Figure 11 shows a schematic of the apparatus with the major components. The filter belt fabric was a HF7-7040 white polyester belt with a 64x24 count in a 6x2 H’bone weave pattern (Clear Edge Filtration). The filter fabric used for gravity settling was the same fabric as the fabric on the crown.

The filter fabric and Crown Press channel were wetted prior to the experiments to minimize losses due to water adhering to the surfaces. After each replication, the equipment was rinsed, to remove any residual solids, and dried. The filter fabric and Crown Press channel were omitted from the drying step.

The wood fine-biosludge slurry was poured into the gravity filter and allowed to filter for 10 minutes. Since no polymer was used to flocculate the sludge, a 10 minute gravity filtering time was necessary to remove enough filtrate from the sample. The sample was then removed from the gravity filter and placed between the two filter belts on top of the crown. The filter belts were pulled over the crown at 100lbs (Crown Press gauge reading) for 30s followed by a quick release, for 150lbs for 30s followed again by a quick release, and then 200lbs for 30s.
Figure 11: Laboratory Crown Press major components

From every replication the following was measured:

1) Volume of gravity filtrate;
2) Volume of total water removed—gravity filtrate plus pressate from mechanical dewatering step;
3) Total solids content of total water collected;
4) DS of Crown Press filter cake.

4.3 Dewatering Test Protocol

For each test, 250ml of biosludge was used. The consistency of the biosludge averaged 1.5% DS. Four different amounts of wood fines were tested to cover the range of reported dosages reported in the literature. Table 3 shows the amount of wood fines used in each test, as well as its corresponding dosage, for the case of oven dry wood fines. Three other moisture contents (MC) were also tested: 35%MC, 64%MC, and 78%MC (these values represent the percentage of water mass of the total mass). The MC of the wood fines tested was chosen to cover the MC range between oven dry and saturation with water. The water saturation point for these wood fines was determined by soaking the wood fines in water for 4 days and measuring the amount
of water absorbed. Testing each wood fine dosage at each MC results in 16 individual experiments. Each experiment was replicated three times.

Table 3: Wood fine addition amounts corresponding dosage for the four tests performed with oven dry wood fines. Each amount was also tested at the three other moisture contents: 35%MC, 64%MC, and 78%MC.

<table>
<thead>
<tr>
<th>Wood Fine Moisture Content [%]</th>
<th>Wood Fine Addition [g]</th>
<th>Corresponding Dosage [g/g biosludge]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>1.9</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>3.9</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>7.7</td>
<td>200%</td>
</tr>
<tr>
<td></td>
<td>11.5</td>
<td>300%</td>
</tr>
</tbody>
</table>

The wood fines used for each experiment were stored in an oven at 103°C to evaporate all residual moisture. The desired amount of oven-dry wood fines was than weighed, and the MC was then changed to the required level by adding the required mass of water. The wood fines were stirred to absorb the water and then added to the biosludge. The resulting wood fine-biosludge slurry was then dewatered with the Crown Press.

4.3.1 Data Analysis

The error bars indicated in the figures within Section 5 (Results and Discussion) represent one standard deviation from the mean. Statistical comparison of the means was performed using the t-test with two degrees of freedom at the 95% level of significance. Simple linear regression analysis of the data was performed using the least squares method.

4.4 Pulp and Paper Mill Field Study

For each experiment, a 12 L sample of biosludge was collected from the secondary clarifier and divided into two equal volumes. A dosage of wood fines was added to each bucket: 0.73 kg dry wood fines/kg DS biosludge for experiments 1 and 2, and 1.35 kg dry wood fines/kg DS biosludge for experiment 3. The moisture content of the wood fines used in the experiments was 63%.

A stock polymer solution of BASF Organopol 5400 (6L, 0.2% consistency) was made one day prior to the experiments. The polymer solution was added to the biosludge-WF mixtures at a dosage of 20kg polymer/ton DS biosludge (960ml of stock solution for these experiments). The
polymer solution was added and the resulting slurry was mixed by decanting the contents into a bucket 2-4 times. Mixing was considered complete through visual observation of the degree of flocculation. Each bucket was then gravity filtered in 250ml batches for approximately 30s.

The gravity thickened sludge from each bucket was combined and gradually poured into the feeding hopper of the laboratory screw press (Figure 12). An auger speed of 8 was used, and the pressure relief cone was adjusted to leave a 1mm gap at the outlet of the machine. Filter cake samples were collected and tested for total solids as per section 4.2.1.

![Figure 12: Laboratory screw press](image)
5 Results and Discussion

This section begins with results that complete an experiment started by a previous MASc student within the research group. The experiment tracks the changes in the sludge bulk properties over time to determine if they substantially change. Next, different amounts of sludge are dewatered on the Crown Press to establish if dry solids content (DS) of the sludge cake is sensitive to the amount of sludge that is dewatered. The wood fines size distribution is characterized by mass; then, visualization of the compressibility of biosludge is presented followed by the results obtained from dewatering samples using the Crown Press. Lastly, experiments that were performed at a pulp and paper mill are summarized.

5.1 Sludge Properties During Transport

Amin [3] had previously confirmed that our research group’s sludge storage procedures do not significantly alter the sludge in the measured parameters of CST, pH, and total solids content. However, these measurements could only be made once the sludge arrived at the University of Toronto. A question remained from that work if the properties of the sludge were altered in the first three days of shipment.

Fresh samples of biosludge, primary sludge A, and primary sludge C were collected and measured over a three day period at the partner mill. For each sludge sample, half was left at room temperature (22°C ±2°C) for the three day period, while the other half was refrigerated (4°C) and then reheated with a warm water bath (22°C ±2°C) prior to testing. Figure 13 shows that the pH of the biosludge remained stable over the test period, and varied within the same range reported by Amin [3]. The measured total solids, not shown, also did not vary significantly during the three day test period, but the absolute values are different than the values reported by Amin. This is understandable because sludge sampled at a different point in time was used and the total solids of the sludge in the treatment plant can vary from day to day as a result of changes in the water treat plant operations and influent streams. Primary sludge A and primary sludge C results are presented in appendix A.
The CST of the refrigerated and room temperature biosludge both increase in the first 24 hours, and then plateau afterwards. An increase in the CST value indicates a decrease in dewaterability, but the initial increase shown in Figure 13 is suspected to be due more to differences in the temperatures that the CST was measured at than changes in the biosludge’s dewaterability. Both the refrigerated and room temperature biosludge samples were tested immediately after they were sampled from the secondary clarifier, which was operating at 36°C. Subsequent CST tests were conducted on the refrigerated and room temperature samples at 22°C ± 2°C.

A mathematical model has been developed for CST that predicts CST to vary linearly with viscosity [40], and viscosity changes with temperature for fluids like water. Water is the main constituent of biosludge and of the filtrate that is being absorbed by the filter paper used in the CST, so increasing the temperature of a sludge sample should decrease the CST because water has a lower viscosity at higher temperatures. To test this, the CST of primary sludge A was collected and refrigerated overnight. The following day, the CST of the sample was measured at 10°C, 22°C, and 35°C (Figure 14).
At 10°C, the viscosity of water is 1.308 cP, and it decreases by 45% to 0.723 cP at 35°C. In Figure 14, the average CST of 80s at 10°C decreases by 60% to an average of 32s at 35°C. Therefore, for this particular sludge, the majority of the changes in CST can be explained by changes in viscosity of water, but there are other factors that are contributing as well to the decreases seen.

These experiments complete the work started by Amin [3], and show that the sludge used by the University of Toronto does not significantly change in the measured values of pH, and total solids in either the short term or long term storage. The CST of the sludge can vary significantly depending on the temperature that the measurements are performed at, so any comparisons between samples should be made at the same temperature. Sampled sludge that is stored at 4°C can be used for experimentation for up to a month from the time of sampling, while still being considered representative of fresh process sludge.
5.2 Pressing Thin Cakes

The Crown Press applies a compressive force to a sludge sample by pulling two pieces of filter belt over a stationary crown. However, if a small sludge sample is being tested, it may be possible that the two filter belts could make direct contact; thus transfer less compressive force through the sludge sample. It is not known if the size of the sample affects how much compressive force is applied to the sludge, and if there is an effect on the final dry solid content (DS) of the filter cake.

Four sample sizes were chosen: 200ml, 300ml, 400ml, and 500ml. All of the samples were dosed with polymer at 20kg/tonne DS, mixed by rapidly decanting the mixture between two beakers six times, and then dewatered with the Crown Press. Figure 15 shows the resulting DS of the filter cakes.

The results show that there is variability in the DS depending on the sample size, but there is no clear dependency between the amount of biosludge that is dewatered and the resulting DS. Thus, the sample size chosen for the work in this thesis, 250ml, is considered to provide representative results.
5.3 Wood Fines

The distribution of the 1.125kg wood fine sample is presented in Table 4. The results show that 70% of the wood fines by mass belong to the 16-35 US mesh size range, and that greater than 10% of the mass pass through a 35 US mesh. This is in close agreement to a similar study using shredded bark, which concluded that for optimum conditioning the majority of the bark needed to be in the 20-40 US mesh size range, and that high solids retention needed at least 10% of the bark to pass a US 40 mesh sieve [34].

Table 4: Distribution of wood fine particle sizes by mass.

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Opening Size (mm)</th>
<th>Mass Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>US 6</td>
<td>3.36</td>
<td>15.8%</td>
</tr>
<tr>
<td>US 16</td>
<td>1.19</td>
<td>44.0%</td>
</tr>
<tr>
<td>US 35</td>
<td>0.50</td>
<td>26.4%</td>
</tr>
<tr>
<td>US 70</td>
<td>0.21</td>
<td>10.0%</td>
</tr>
<tr>
<td>&lt; US 70</td>
<td>N/A</td>
<td>3.7%</td>
</tr>
</tbody>
</table>

5.4 Visualizing Compressibility of Biosludge

The first attempts to visualize the compressibility of biosludge were done using a fabricated viewing apparatus, Figure 16, and raw biosludge. It was intended to use the viewing apparatus under a microscope to observe the buildup and compression of the filter cake, but a few problems with this approach became apparent.
Figure 16: Apparatus used to visualize biosludge compression

The biosludge slurry was too opaque and blocked all light transmission on the filter cake side of the filter, making it impossible to locate the filter cake-slurry interface. A polymer could not be used to flocculate the biosludge because the resulting flocs would have been too large to pass through the tubing. Reducing the floc size would have made them smaller than the typical sizes in industry. Also, any filter aid that would have been of interest to study would also have to be reduced to a small enough size to pass through the tubing.

The limited field of view that the microscope would have provided was also a concern. In order to see sufficient detail, the field of view would have been limited to the interface of the filter media and the filter cake. Due to the limited field of view, the development of the entire filter cake would not have been possible.
Using a polymer for observation studies is crucial because it clarifies the slurry to make light transmission, and visual observation, possible. A flocculated slurry is also more representative of a slurry being filtered by industrial dewatering machines. Small samples of flocculated biosludge were filmed undergoing vacuum filtration in a larger apparatus and compared to flocculated biosludge-wood fine (biosludge-WF) mixtures.

Comparing the filtering of biosludge with and without wood fines clearly shows the dewatering benefits commonly reported in the literature: a faster rate of filtration and a reduction in compressibility. In Figure 17, the biosludge sample filters slower than the biosludge-WF mixture. At $t = 45s$ the majority of the water has been removed from the biosludge sample, but it is still being compressed up until the end of filtration at $t = 60s$. The biosludge-WF mixtures has most of the water removed at $t = 30s$, Figure 18, and does not substantially change its volume after this point in time.
Figure 17: Vacuum filtration of biosludge video still frames from 0s to 60s

Figure 18: Vacuum filtration of biosludge-WF mixture video still frames from 0s to 60s
Under vacuum filtration, the wood fines are clearly reducing the amount that the biosludge is being compressed, which maintains the porosity of the filter cake and increases the rate at which the filtrate is removed. Despite this benefit, the amount of filtrate recovered in both cases is approximately the same. A possible explanation as to why more water is not recovered may be due to the lack of mechanical pressure to express the filter cake. A vacuum will become ineffective at expressing the cake as soon as cracks form through the cake and a strong vacuum can no longer be maintained. To further investigate the role that wood fines play in the dewatering of biosludge the Crown Press will be used.

5.5 Dewatering Wood Fines with the Crown Press

The Crown Press was used to perform dewaterability assessments on biosludge-WF mixtures. Adding a polymer can significantly improve the dewaterability characteristics of biosludge; however, a polymer was not used in these experiments so any change in the dewaterability of biosludge could be attributed to the wood fines. A mass balance was performed on each experiment replication; the calculations and assumptions made are presented in Appendix B.

The results in this section are primarily plotted with the dosage of wood fines on the x-axis. Dosage is a weight percent, and it represents the dry mass of wood fines per dry mass biosludge. For example: if a 250ml sample of biosludge contains 4g of dry mass, then wood fine dosages of 50% and 200% would mean 2g and 8g of wood fines are added respectively.

5.5.1 Dewatering Biosludge with Oven Dry Wood Fines

The DS of the filter cakes increases with each successive increase in wood fine dosage (Figure 19). The data can be described by a polynomial equation that suggests the DS of the cake approaches a maximum DS, which would be the DS of water saturated wood fines. This is in agreement with Marshall et al.[34], who postulated that the maximum DS achieved using shredded bark would likely be that of shredded bark saturated with water.
Figure 19: Dry solid content of biosludge-WF filter cakes with increasing dosage of oven dry wood fines.

Only measuring the DS of the filter cake does not provide any information on how the DS is increasing. The DS can be increasing because more biosludge solids are being captured, the wood fines are assisting with the removal of water, or the DS is increasing simply because wood fines are being added. By conducting a mass balance on the biosludge particles, and measuring the total volume of water collected at each dosage of wood fines, a conclusion can be made on the relative contribution each component makes to the increase of the DS of the filter cake.

The mass balance reveals that the dry mass of biosludge solids in the total water collected does not significantly change with increasing dosages of wood fines (Figure 20). This means that the wood fines do not help to capture and retain more biosludge particles during dewatering. The amount of biosludge solids in the filter cake is determined by weighing the entire dry mass of the filter cake and subtracting the dry mass of wood fines that was added. Figure 20 shows that biosolids in the filter cake increases by 1g on average when the wood fines dosage is increased from 0% to 300%. The increase in biosolids in the filter cake is caused by an improvement in cake release properties.
Figure 20: Dry solids content of the filter cake and the dry mass of biosludge solids in the filter cake and total water collected with increasing dosages of oven dry wood fines.

Figure 21 shows that as the dosage of wood fines is increased, less biosludge adheres to the filter media; thus, increasing the amount that is measured in the filter cake. Wood fines can help to improve the dewaterability of biosludge at high dosages by acting as a filter aid, improving the filter cake release properties, but this improvement is small. At a dosage of 300% used in this study, 11.55g of wood fines were added to yield a 1g increase in biosludge solids within the filter cake. Therefore, the increase in biosludge solids plays only a minor role in the overall increase of the filter cake DS.
To determine how much of the increase in DS is due to more water being removed, the total volume of water collected is examined. Figure 22 shows how the total volume of water collected continuously decreases with each successively larger dose of wood fines. Less water is being collected because the wood fines are absorbing the free water within the slurry, allowing less to be collected. Since the total volume of water collected at each wood fine dosage is less than when no wood fines are used, the increase in the filter cake DS is not due to the wood fines allowing more water to be released.
Wood fines do not lead to the release of more water, and they only increase the amount of biosolids in the filter cake by a small amount relative to the amount of wood fines added; therefore, the increase in the DS of the filter cake is mostly due to the wood fines being added. Overall, oven dry wood fines do not function as a skeleton builder, but instead, as a bulking agent.

However, a high DS is desired for incineration and to meet the minimum DS regulations of the local landfill. It can be argued that although the wood fines are not functioning well as a skeleton builder, their usage is still justified because the DS of the filter cake is increasing. This is true, but adding wood fines (and the water they absorb) increases the mass that has to be handled after the dewatering operations. Therefore, each dewatering plant must perform an economic analysis to determine if the increase in mass of the wood fines and absorbed water is justified by the increase to the DS of the filter cake. This is particularly important if landfilling is the principal means of disposal because tipping fees, and dump truck load weight restrictions, are calculated by mass not by volume.
To understand how much the mass of the filter cake is affected, the total wet mass of recoverable filter cake was recorded for each wood fine dosage. Figure 23 shows the percentage change in total mass of biosludge-WF filter cakes compared to a filter cake that is just comprised of biosludge. The dry mass of each filter cake was also measured, which enables the total mass to be compared to the mass of water that is present in the filter cake. From these results it is seen that the water absorbed by the wood fines is responsible for the majority of the total mass increase. The difference between the total mass and the water mass is the mass of the dry solids, which is comprised of biosludge solids and wood fines.

Figure 23: Effect of adding wood fines on the total change of the filter cake mass.

Wood fines are rarely, if ever, oven dry. Normally, the wood fines come directly from the chipping operations where trees are freshly harvested or air-dried, or they are stored in temporary piles outside where they are subject to wind, rain, and snow. It is important to study how wood fines of different moisture contents (MC) would function as filter aids because this is more realistic of industrial conditions.
5.5.2 Dewatering Biosludge with Wood Fines of Varying Moisture Content

The Crown Press experiments were repeated with wood fines with MC of 35%, 64% and 78%MC. Figure 24 is plotted with these results along with the results from the experiment with the oven dry wood fines (0%MC). Each MC tested follows the same trend as the 0%MC wood fines, and only half of the DS measured as statistically different from the 0%MC values.

Figure 24: Effect of wood fine MC in biosludge-WF mixtures on the filter cake DS.

Figure 25 and Figure 26 show amount of biosludge solids that were measured in the total water and filter cake respectively. The dry mass of biosludge solids was similar across all of the different wood fine MC, which means that the MC of the wood fines does not influence the capture efficiency of biosludge solids. Moreover, all of the wood fine MC tested exhibit a similar trend for the amount of biosludge measured within the filter cake: as more wood fines are added, the filter cake release properties improve and less biosludge particles are lost in the filter media.
Figure 25: Effect of wood fine MC on dry mass of biosludge in total water collected for various wood fine dosages.

Figure 26: Effect of wood fine MC in biosludge solids in the filter cake for various wood fine dosages.

The volume of water collected from each experiment is plotted in Figure 27. With the exception of the most saturated wood fines, 78% MC Fines, Figure 27 shows two trends. The
first trend is: the volume of water collected decreases as more wood fines are added. As more wood fines are added, a larger volume of water must be absorbed for all of the wood fines to reach their moisture saturation point. Since more water is absorbed, there is less water left to be collected. The second trend, wood fines with a higher starting MC collect more water, is also explained by the wood fine’s moisture saturation point. Wetter wood fines have less absorption capacity than drier wood fines, so they will absorb less water from the sludge and more water will be collected.

![Figure 27: Effect of wood fine MC in biosludge-WF mixtures on the total volume of water collected.](image)

The 78%MC Fines collected the more water at the two highest dosage levels, 200% and 300%, than when no wood fines were added. The extra water, approximately 10ml, could be from oversaturating the fines with water. The additional water would then just be excess surface water on the fines and not extra water that the fines help to release from the biosludge. To determine if this is true, an additional experiment was conducted using saturated wood fines.

### 5.5.3 Saturated Wood Fines

Wood fines were soaked in water over night and dewatered on the Crown Press to remove the excess water. The moisture content of these wood fines is between 72-75%MC. A mass of the saturated wood fines was then added to a sample of biosludge (solid consistency of 1.79%) and
dewatered with the Crown Press. The wet weight of wood fines was chosen so that the dry weight would be approximately the same as the dosages tested in the initial experiments. The volume of filtrate, pressate, and total water collected is plotted in Figure 28.

![Figure 28: Volume of filtrate, pressate, and total water collected from a biosludge-WF mixture made with saturated wood fines.](image)

The volume of filtrate collected at each dosage level is not significantly different, but the volume of pressate collected increases when the dosages of wood fines is 200% or greater. This suggests that at this and higher dosages, wood fines are reducing the compressibility of biosludge and allowing more water to be released. However, this volume of water is only about 5ml. Combining these two volumes produces a similar trend as was shown for the 78%MC fines in Figure 27: a small increase in total water at higher wood fine dosages. This result, along with the fact that wood fines only became saturated to 72-75%MC after soaking overnight, support the idea that the 78%MC Fines were oversaturated in the initial experiment, which leads to the excess water appearing as additional filtrate, about 5ml. The total amount of water collected in this experiment is lower than in the initial experiment. This is believed to be due to differences in the sludge, as this experiment had to be performed with a sample of sludge that was collected 6 months after the initial experiment.
The water that is absorbed by the wood fines largely remains within the wood fines during dewatering with the Crown Press. To quantify how much water remains per gram of wood fines, three samples containing 14g of oven dry wood fines and 250ml of water were soaked overnight. The three samples had an average DS of 24.4% after Crown Pressing, and collected an average total volume of water of 193ml. The filter cakes had an average water content of 38.6ml (at 1ml/g water), which means each gram of wood fines absorbed 2.8ml of water on average.

The amount of water absorbed by the wood fines is also dependent on the type and size distribution of the individual particles. When allowed to soak and become completely saturated, sawdust will absorb the most water, followed by softwood species, and finally hardwood species [4].

5.5.4 Discussion on Using Wood Fines as a Physical Conditioner

When assessing a physical conditioner to be used in biosludge dewatering, it is important to evaluate the amount of water collected as well as conduct a mass balance to determine where the biosludge solids are going. Relying solely on the dry solid content or the rate of filtration—as measured by visual observation, the SRF test, or the CST test—can give only partial results. This study started with a visual observation of how wood fines reduce the compressibility of biosludge as well as increase the rate of filtration. Also, adding wood fines clearly increases the DS of the filter cake. These three results agree with the most recent published literature that have added wood products to biosludge [5, 32, 33]. However, this study went on to evaluate that amount of biosludge solids that were captured and found no improvement except that the wood fines decreased the amount of biosludge that adhered to the filter media. Most importantly, this study also found that wood fines absorb more water than they help release, unless the wood fines are first completely saturated with water, which results in less overall water being removed from the slurry than if no wood fines were used.

Therefore, wood fines don’t improve all aspects of biosludge dewaterability, and their benefits must be weighed against their consequences. The primary consequence is the volume of water that is absorbed by the wood fines, which decreases the amount of water this is able to be removed as well as increases the total mass of the filter cake to be disposed of.
Limiting the amount of time that the wood fines are within the slurry will decrease the amount of water absorbed and lessen the adverse effects. A low soak time is likely one reason why wood based physical conditioners are viewed favorably in the literature. However, a low soak time is not practical in industry. Typically at a pulp and paper mill, all of the separate sludge streams and the wood fines are combined in a mix tank prior to being dewatered. In Canadian mills, the retention time of the mix tank can vary from 10 minutes up to several hours [17].

Moisture saturated wood fines do show some improvement in dewaterability at a high dosage, but using only saturated wood fines is not practical. Since wood fines are commonly stored outside in large piles, they will dry naturally. In this study, the higher dosages of wood fines that were moisture saturated only released an extra 5ml of water, and wood fines that were at a high MC of 64% absorbed more water than they helped release. Even with a MC of 64%, water would have to be added in order to saturate the fines, which is illogical given the whole purpose of dewatering is to remove water.

To achieve higher DS it is better to add wood fines after the biosludge has been dewatered. Figure 29 shows wood fines with two different moisture contents mixed with dewatered biosludge. The oven dry wood fines had a higher DS than oven dry wood fines that were first mixed with the biosludge and then dewatered. This is because there is minimal water available in the dewatered biosludge that can be absorbed by the wood fines. Minimum regulated DS for landfills can be achieved by using less fines, or, if incineration is the final means of disposal, adding wood fines to the biosludge after it has been dewatered will have less of an adverse impact on the wood fines heating value.
Figure 29: Comparison of filter cake dry solid contents from mixing wood fines before and after biosludge is dewatered.

Good dewatering characteristics involve more than a high DS. Cake release properties are also very important because the filter belt on an industrial machine must be washed every revolution. A poor releasing sludge will make the belt dirty, which will require more high pressure water to clean it. Not only does this increase energy usage from the pumps used to move the water, but the extra wash water must be treated by the wastewater plant. This increases the loading on the plant in both volume as well as solids because more solids are handled twice. Adding wood fines does help to improve the release properties of biosludge and makes the resulting filter cake easier to handle.

The skeleton builder effect that physical conditioners can create is analogous to a composite material like fiberglass reinforced plastic. The fiberglass provides the strength and the plastic holds the fiberglass fibres in place and transmits the applied forces to them. Biosludge, however, is too weak of a material to transmit forces effectively, so the only way a force can be transmitted between the fibres is if they make physical contact with each other. There is evidence from the amount of pressate from the saturated wood fines experiment that the wood fines do function as a skeleton builder when they exist in great enough numbers. A possible
explanation as to why the wood fines are not functioning as a skeleton builder at lower dosages may be because they are too large and exist in too few numbers to form an effective network that would transfer the compressive forces to the biosludge particles. The following section compares the dewaterability of biosludge mixed with wood fines and pulp fibres obtained from a primary sludge.

5.6 Comparing Primary Sludge Fibres to Wood Fines

The fibres within primary sludge (PS) are individual cellulose and hemicellulose fibres from the pulp and paper mill’s pulping operations. Wood fines are screening rejects from the pulp and paper mill’s chipping operations. Figure 30 and Figure 31 show the large discrepancy in individual fibre size between wood fines and PS fibres respectively. Additionally, the figures show that the PS fibres tend to clump together and are difficult to separate. The smaller fibre size and the tendency to agglomerate are thought to be beneficial in producing a skeleton builder effect. Also, the greater individual number of PS fibres on a dry weight basis should allow for more individual fibre-fibre interactions.

![Figure 30: Oven dried wood fines](image1)

![Figure 31: Oven dried PS fibres](image2)

5.6.1 Dewatering Biosludge with PS Fibres and Wood Fines: No Polymer

Biosludge with a solids content of 17.3 g/l (1.7% DS) was dewatered along with separate mixtures of biosludge plus PS fibres (biosludge-PS) and biosludge plus wood fines (biosludge-WF), both at dosages of 50%. A dosage of 50% was chosen because no significant effect was evident from the wood fines from the above experiments; if the biosludge-PS mixture performs
differently at this dosage, then particle size and number are important factors when selecting filter aids. A polymer was not used for this set of experiments.

Figure 32 shows the volume of gravity filtrate collected from the three mixtures. While the biosludge and biosludge-WF mixtures collect a similar amount of filtrate, the biosludge-PS mixture collects less. This suggests that the PS fibres are altering the cake structure to make it less permeable to water flow, where the wood fines do not appear to be producing any change. A possible explanation for difference between the PS fibres and the wood fines is the wood fines are too coarse and/or exist in too few numbers to interact with each other to produce a change in cake filtering properties. However, the change produced by the biosludge-PS mixture is the opposite of what is expected to happen: instead of increasing the permeability of the filter cake the PS fibres decreased it.

Figure 32: Gravity filtrate collected and dry solid content of filter cake from biosludge, biosludge-PS, and biosludge-WF mixtures.

When the water that is collected from dewatering the mixtures in the Crown Press is added to the gravity filtrate, the biosludge-PS mixture collects the most water (Figure 33). So despite retaining more water during gravity filtration, this retained water is readily released when pressure is applied. And similar to the gravity filtrate results, there is no statistical difference
between the total amount of water collected between the biosludge and biosludge-WF mixtures. This suggests that there are too few wood fines, or perhaps they are too coarse, to alter the dewatering properties of biosludge.

![Graph showing dry solids content and total volume of water for biosludge, biosludge-PS, and biosludge-WF mixtures.](image)

**Figure 33:** Total volume of water and the dry solid content of the filter cakes for biosludge, biosludge-PS, and biosludge-WF mixtures.

Although the biosludge-PS mixture dewatered to a greater extent than the biosludge-WF mixture, it has a lower filter cake DS. The dry mass of PS fibres and wood fines added is the same in both mixtures, and it is assumed that all of the physical conditioner is captured and retained in the filter cake. Differences in the DS of the filter cakes have to be explained by the amount of biosludge particles captured.

Figure 34 shows the DS of the filter cakes, the amount of biosludge solids measured in the total volume of water collected, and the calculated biosolids in the filter cakes for the three mixtures. Both the biosludge and biosludge-WF mixtures have a similar amount of biosolids in the collected water, but the biosludge-PS mixtures has 50% less. This suggests that the PS fibres are forming a tightly woven network which is able to retain biosludge particles better than just the filter media. Moreover, there are five times more biosludge solids in the biosludge-PS filter cake than either the biosludge or biosludge-WF filter cakes. This is because
the PS fibers substantially improved the filter cake release properties so less biosludge solids were lost as a result of being lodged in the filter media.

A principal reason why the DS of the biosludge-PS filter cake is lower than the biosludge-WF filter cake is because of the higher capture efficiency of biosludge particles. The mass balance of the biosludge mixture reveals that every gram of biosludge solids in the filter cake contains 14.6g of water on average. Since the biosludge-PS filter cake has more biosludge particles, there will be more water within the filter cake as well. A comparison of the amount of water in the three filter cakes is shown in Figure 35. The biosludge-PS filter cake contains on average 1.3g of biosolids more than the biosludge-WF filter cake, and has on average 11.6g more water. The amount of biosolids is not the only contributing factor to the differences in the filter cake’s water content. It is suspected that the wood fines absorb more water than the PS fibers, which cause the biosludge-WF filter cake to contain more water than calculated based on biosolids content.
Figure 35: Water content and the dry solid content of filter cakes and from biosludge, biosludge-PS, and biosludge-WF mixtures.

The work above can be interpreted in two ways depending on what is meant by dewaterability. If the dry solid content is the main metric used to evaluate dewaterability, which is often the case, then the biosludge-WF mixture would be deemed superior. However, the biosludge-PS mixture allowed for more water to be released, and captured a higher amount of biosludge solid particles, and improved the cake release properties. This discrepancy in interpreting the results highlights the complexity of evaluating dewaterability found in the literature, and the pitfall of relying on a single measurement such as the DS of the filter cake, especially when evaluating physical conditioners.

It is clear that number of fibres and their size do matter when a polymer is not used. The smaller and more numerous PS fibres captured more biosludge particles, released more water, and improved cake handling properties than the wood fines at the same dosage. It is plausible that further refining of the wood fines would improve their performance since PS fibres are essentially highly refined wood chips.

The above experiments were performed without a polymer to be able to determine the effect of the fibres, but this is not realistic for industrial dewatering. A polymer is always used to
destabilize the biosludge colloid and agglomerate the individual biosludge particles into larger flocs. This greatly increases the rate of filtration, produces a filtrate with low total solids, and produces filter cakes with a higher DS. Additionally, as mentioned in the Literature Review section, physical conditioners perform better with a polymer. For the next set of experiments a polymer was added to each mixture before it was dewatered.

### 5.6.2 Dewatering Biosludge with PS Fibres and Wood Fines: with Polymer

Biosludge with a solids content of 15.5 g/l (1.55% DS), biosludge-PS and biosludge-WF mixtures, both at dosages of 100%, were mixed with a polymer and dewatered. A higher dosage of 100% was used in order for there to be enough wood fines present in the mixture so a measurable amount of water would be absorbed by the wood fines. The biosludge-PS and the biosludge-WF were allowed to soak for 10 minutes prior to adding polymer to allow the fibres to become saturated with water as they normally would in industry. A stock solution of polymer (BASF Zetag 8165) was prepared (0.5% solids consistency), and 15.5ml was added to each mixture prior to dewatering (20kg/tonne DS biosludge). After adding the polymer, each mixture was mixed rapidly by decanting the contents between two beakers six times.

The mixtures were then gravity filtered for approximately 15 seconds, stirring once to simulate a plow on a gravity table, and then transferred to the Crown Press for mechanical dewatering. One reason to add physical conditioners is to allow for a higher pressure to be applied. The highest press regime that could be applied to the biosludge was 100-150-200psig, but the biosludge-PS and the biosludge-WF mixtures could withstand a higher press regime of 150-200-250psig, so this higher press regime was used on these two mixtures.

Similar to the results in the previous section, the biosludge-PS mixture collected the least amount of gravity filtrate, Figure 36. This is likely due the individual PS fibres forming a tight network and trapping water within the flocs. The biosludge mixture collected the most water. This was expected because it was anticipated that the wood fines would absorb some water, and, from the results in section 5.5, are thought to be too large or too few in number to form a network similar to the PS fibres. There is no statistically significant difference between the DS of the biosludge-PS and the biosludge-WF filter cakes.
Figure 36: Gravity filtrate collected and the dry solid content of filter cakes from biosludge, biosludge-PS, and biosludge-WF mixtures mixed with polymer.

There is also no statistical difference between the total volumes of water collected from each mixture, Figure 37. Interestingly, the combination of adding physical conditioners and using higher pressures on both the biosludge-PS and the biosludge-WF mixtures did not remove more water than just adding polymer to the biosludge. An explanation for this could be the combination of absorption, adsorption, and entrapment of water within the flocs by the physical conditioners.
Adding physical conditioners did not reduce the amount of biosolids in the total water collected, which means the added polymer was primarily responsible for improving biosolids capture efficiency (Figure 38). The average mass of biosolids in the filtrate, 0.4g, is 43% lower than the best performing mixture that was tested without a polymer (biosludge-PS with an average of 0.71g biosludge solids in the filtrate). Both the biosludge-PS and the biosludge-WF mixtures had good cake release properties and had a similar amount of biosludge solids in the filter cake (Figure 39).
The above results indicate that neither the wood fines, nor the PS fibres are functioning as a filter aid (higher biosludge particle capture). While they do allow for more pressure to be applied during dewatering (skeleton builder effect), the higher applied pressure does not result in more water being squeezed out of the filter cake than just biosludge and polymer. Both
mixtures release the same amount of water, and both have the same amount of water retained in the filter cake (Figure 40). Since both the biosludge-PS and the biosludge-WF mixtures have a higher filter cake DS, the increase must be primarily due to the added physical conditioners.

![Graph showing water content and DS of filter cakes from biosludge, biosludge-PS, and biosludge-WF mixtures mixed with polymer.](Image)

**Figure 40:** Water content and DS of filter cakes from biosludge, biosludge-PS, and biosludge-WF mixtures mixed with polymer.

A possible explanation as to why both the PS fibres and the wood fines do not release more water than the biosludge mixture may be because both fibres are too large compared to the size of the biosludge particles. Instead of the compressive forces being transferred via a fibre-biosludge-fibre route, they are transferred only fibre-to-fibre. In Figure 41, a cross-section of the biosludge-WF filter cake shows the wood fines arranged on top of one another in layers. The biosludge fills the spaces between the wood fines within the depth of each layer. When the compression force is applied, the wood fines take all the load and pass it directly through the filter cake without compressing the biosludge. A similar effect is believed to also be occurring in the biosludge-PS filter cake. However, as can be seen in Figure 41, the individual fibres are not arranged in layers, but rather interwoven into a tight network.
This network is shown under higher magnification in Figure 42. In this photo it can be seen that the biosludge particles are still within the spaces created by the PS fibres, and that the fibres are much larger than the individual biosludge particles. The fibre network appears to be continuous enough to transfer the compressive forces directly between the fibres without affecting the biosludge particles.
A lower dosage of PS fibres (50%) was added to biosludge and dewatered to test if having fewer fibers would transfer more compressive force to the biosludge particles and release more water. compares the DS of the filter cake and the total volume of water collected of this new mixture and biosludge. The measured DS of the biosludge-PS50 filter cake is higher than the filter cake of biosludge and polymer, while the total volume of water collected is not statistically different between the two mixtures (Figure 43). In the filter cake, there are more biosludge particles for the biosludge-PS50 mixture than the biosludge mixture (3.8g compared to 2.8g respectively).
At this lower dosage level, there is a balance between the amount of water that is absorbed by the PS fibres and the amount of water that the PS fibres help to release. As well, the cake handling properties are improved to an acceptable level: the filter cake handling properties are comparable to that shown in Figure 39 for biosludge-PS at a 100% dosage.

Adding PS fibres is affected by diminishing returns. The incremental increase to the biosludge filter cake DS at the 50% dosage level is 6% (from 15.1%DS to 21.1%DS), but when the dosage is increased from 50% to 100% the increase in the dry solid content is only 1.5% (from 21.1%DS to 22.6%DS). This agrees with Amin’s [3] findings. In his experiments, the increases in the DS of the filter cake were greatly reduced beyond PS solids content of 40% in the slurry (a dosage of about 35%).
5.7 Dewatering Wood Fines with a Laboratory Screw Press

The Crown Press, which simulates a belt filter press, was used for the above experiments. Another common industrial dewatering machine is the screw press. As part of this research a pulp and paper mill was visited in August 2014 to conduct experiments with the mill’s laboratory screw press.

The DS of the filter cakes from the three experiments is presented in Table 5. Compared to the DS of similar biosludge-WF mixtures in section 5.6.2 (22.7% DS), the screw press performed much worse than the Crown Press.

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Wood Fine Dosage [g/g biosludge]</th>
<th>Average Filter Cake DS [%]</th>
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</thead>
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<tr>
<td>1</td>
<td>70%</td>
<td>10.1</td>
</tr>
<tr>
<td>2</td>
<td>70%</td>
<td>10.8</td>
</tr>
<tr>
<td>3</td>
<td>135%</td>
<td>13.2</td>
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</table>

To test if the sludge or different polymer were causing the poor performance, a 300ml sample from the third experiment was also dewatered on the Crown Press. A filter cake DS of 21% was measured, which is comparable to results obtained in section 5.6.2. A possible explanation for the discrepancy between the filter cake DS obtained from the Crown Press and the screw press is how the two dewatering devices operate.

During the laboratory screw press operation, the wood fines repeatedly clogged the outlet of the screw press (Figure 44). The pressure relief cone provides back pressure for the machine so the sludge can be compressed between the screen housing and the threads of the screw. If it is too loose, insufficient backpressure is applied to dewater the sludge, and the screw press merely operates as a conveyor. The tendency of wood fines to clog the screw press is also reported by the operators of the industrial scale screw presses at the mill.
Figure 44: Wood fines building up at the pressure relief cone and clogging outlet of the screw press.

Since the outlet of the screw press is clogged with wood fines, the movement of the biosludge flocs through the screw press is restricted. The screw continues to rotate and mechanically reduces the size of the biosludge flocs until they are small enough to flow through the screen housing and ended up in the pressate of the machine. Figure 45 shows the difference between the clean screen housing of the screw press and the dirty screen housing after one of the experiments was complete. The buildup of biosludge flocs at the outlet of the machine is clearly visible (right hand side of images).

Figure 45: Photo of clean screw press screen housing (left) and dirty screen house (right).

Biosludge flocs are fragile and need to be expressed carefully or they will be reduced in size. The Crown Press performed better because it applies less shear to the flocs, and does not apply the shear forces continuously. Also, the sludge is mostly stationary in the Crown Press; whereas the screw press continuously moves the sludge. Industrial screw presses typically do
not perform as well as belt filter presses when dewatering biosludge, and do best with sludges that are high in fibre. This laboratory screw press can regularly dewater the mill’s sludge to a filter cake DS of 35% because the mill’s sludge averages 70% PS by volume, which has a high fibre content.

This experiment illustrates that the type of fibre is also important when selecting the type of dewatering equipment to be used. Wood fines are too coarse and rigid to be used in a screw press. They do not provide any dewatering benefit and tend to create operational difficulties. PS fibres are smaller, more flexible, and exist in greater numbers for a given dry mass. This enables them to move with the biosludge and provide enough rigidity to withstand the pressures of the screw press without having the size of the flocs reduced.
6 Implications

This research presents a few findings which required further elaboration and the implications in an industrial setting.

When mixed with a polymer, both the wood fines and the primary sludge (PS) fibres removed less water than the control mixture of just biosludge and polymer. This suggests that the increases in the dry solid content (DS) of the filter cakes observed in industry when PS is added is due to the dry solids of the PS fibres, and not because more water is removed.

The PS fibres and the wood fines improved the filter cake release properties, which is an important dewatering characteristic for industry to improve because the sludge will be easier to handle. For example, a filter cake that detaches from the filter media easily will require less washing water, and the filter media will remain permeable to water for a longer period of time. A lower dosage of PS fibres was needed to achieve better cake release properties than wood fines, regardless if a polymer was used.

The PS fibres in primary sludge are already saturated with water; therefore, it is more practical to add PS fibres than wood fines because they will not absorb any more water from the biosludge. This study did not attempt to quantify the amount of water that water saturated PS fibres help release from the biosludge. Again, since the PS fibres are already saturated with water, any benefit caused by the PS fibres will be an improvement to dewatering operations. This is not the case when wood fines are added because wood fines can absorb more water then they help release, causing a net decrease in water removal.

Adding wood fines to biosludge also decreases the heating value of the wood fines because now there is more water to evaporate before combustion can commence. A higher filter cake DS can be achieved if the biosludge is dewatered first and then mixed with wood fines. The mill visited as part of this research mixed wood fines before dewatering because the mix tank provided good dispersion and it was convenient given the layout of the dewatering plant. To mix the wood fines after dewatering would require another piece of equipment and the inherent operating costs and logics. This situation is likely similar at other mills.
Although the wood fines absorb water, which decreases their heating value, they create a more porous filter cake that may actually be beneficial for incineration due to faster drying times and less clumping. An assessment of how well biosludge dries with various dosages of wood fines needs to be performed, and then both the drying operations and the dewatering operations need to be evaluated together to determine if adding wood fines before dewatering is beneficial to the entire system.

It is possible that the filter belt fabric used in this study may affect cake release properties, and thus the rate of filtration and the ultimate dry solids achieved.

Finally, a different mixture of wood fines than what was used in these experiments could produce different absolute results. A higher distribution of larger chips could absorb water more slowly due to the lower surface area to volume ratio, and they would pack less densely. Also, hardwood species have a lower moisture saturation point than softwood species, so the effect on the mass of the filter cake will be less. However, the amount of water released due to the wood fines reducing compressibility is small compared to the amount of water that is absorbed, so the findings in this thesis will still apply.
7 Conclusions

The primary objectives of this thesis were to evaluate wood fines as a physical conditioner for biosludge dewatering and compare how it performs to primary sludge fibres. A secondary objective was the direct observation of biosludge filtration. The following is a list of specific conclusions that were made based on the results contained within this thesis:

1) Wood fines can increase the rate of filtration, and reduce the compressibility of the mixture. This is in agreement with results from recently published studies evaluating wood based physical conditioners. These studies also found that wood based physical conditioners can increase the dry solid content (DS) of the filter cake, but there is insufficient information to understand how the DS of the filter cake is increased. In this study, a mass balance revealed that the increase in the DS of the filter cake is primarily caused by dry mass within the wood fines.

2) Adding wood fines can help improve the cake handling properties of biosludge. Having better cake handling properties means more biosludge solids will be retained in the filter cake instead of being lodged in the filter media. Using a polymer requires less wood fines to be added to achieve similar cake release properties. A mixture of biosludge, polymer, and wood fines at a 100% dosage had better cake release properties (as measured by the percentage of initial biosludge solids retained in the filter cake) than a mixture of biosludge and wood fines at a 300% dosage without a polymer.

3) When evaluated without a polymer on the Crown Press, the starting moisture content of the wood fines only affected the amount of water they absorbed from the biosludge, with the more saturated wood fines absorbing less water.

4) A filter cake with a higher DS can be achieved if the wood fines are mixed into the biosludge after it is dewatered. This is because there would be less free water available to be absorbed by the wood fines.

5) Wood fines perform differently depending on the dewatering equipment used. A higher filter cake DS was obtained using the Crown Press than on a laboratory screw press (21% vs. 13.1%). This suggests that wood fines are more suitable as a physical conditioner in dewatering equipment where the sludge is stationary relative to the filter media.
6) Although it is visually observed that wood fines reduce the compressibility of biosludge, the mass balance found this benefit to be small. When the wood fines are completely saturated with water, and a dosage of 300% is used, 5ml of extra water is removed. This is small in comparison to the moisture absorption capacity of wood fines, which is measured to be 2.8g of water per gram of dry wood fines. Even when a polymer is used and a higher dewatering pressure is applied, the wood fines failed to help release more water than what could be obtained from just biosludge and polymer.

7) When mixed without a polymer, primary sludge (PS) fibres performed better as a dewaterability aid than wood fines. More biosludge solids were captured, more water was removed, and the filter cake release properties were better.

8) When mixed with a polymer, there is no noticeable difference between PS fibres and wood fines when biosludge is dewatered on a Crown Press except in the amount of gravity filtrate recovered.

9) Wood fines do decrease the compressibility of biosludge and increase the rate of water removal; however, the extent of both parameters were not quantified. Direct observation of the filtration of biosludge is a difficult task due to the colloidal nature of the material and the small particle sizes involved.
8 Future Work and Recommendations

1) Future research in the assessment of physical conditioners should always involve a mass balance, and it is important to look at multiple performance parameters when evaluating dewaterability (filtration rate, DS content, particle capture, extent of water removal, cake release properties, as well as technical and economic considerations). This is especially important if the solids have a high capacity of moisture absorption.

2) Wood fines may be beneficial in assisting in gravity filtration or low pressure dewatering such as vacuum filtration. Primary fibres caused a decrease in the amount of gravity filtrate collected both with and without a polymer, which suggests there is a limit in the size of physical conditioners before adverse effects occur. It is recommended to conduct filtration rate studies for these two dewatering operations and determine if wood fines are beneficial as a gravity filtration aid. A model could be developed for the filtration process to describe how the size of the physical conditioner affects the filtration process. The problem of water absorption will still require management, and the wood fines should be added before the polymer is added because mixing should be minimized after a polymer is added so the flocs are not destroyed.

3) A reduction in the particle size of the wood fines may decrease operating issues (plugging) when dewatering with a screw press. It is recommended to test this using wood fines that are less fibrous and have smaller aspect ratios.

4) To supplement primary sludge fibres, a portion of the dewatered sludge could be added into the process. This may be especially beneficial for sludges that are already quite fibrous. Studies will have to determine how much to add and if the sludge becomes suspended in water or if it maintains its shape and provides dewatering benefits.

5) Partially dewatering primary sludge separately from biosludge and using a portion of the sludge to make the biosludge manageable is another dewatering alternative. Primary sludge dewatered readily, and can resist higher operating pressures than biosludges. It is possible that dewatering the two streams separately can remove more total water than when dewatering the two combined streams. This will have to be considered with the increase in operating logistics and changes in chemical requirements.

6) Adding wood fines increases the add bulk material to the biosludge, and the porous structure created may make it more favorable for downstream drying operations. Since
is easier to mix wood fines into biosludge within the mix tank than after the biosludge is dewatered, the drying of biosludge-WF mixtures should be performed so that a complete statement can be made about the benefits of adding wood fines.

7) The net yield equation is not believed to represent a true evaluation of the physical conditioners, however there is insufficient evidence contained in this thesis to support this. It is a popular evaluation criteria amongst researchers, and it would be important to understand if the equation is evaluating physical conditioners properly.
9 References


Primary sludge A showed no significant change to pH over the course of the experiment and CST for the refrigerated sample, Figure 46. Due to the high fibre content of this sludge, it has a much higher total solids content than the other two sludges studied, and cooled much slower. This is why the long term CST results vary considerably from the initial measurements. Total solids, not shown, did not vary significantly over the course of this experiment.

Figure 46: Variation of primary sludge A CST and pH over three day test period

Primary sludge C showed no significant change to pH over the course of the experiment and CST for the refrigerated sample, Figure 47. This was the coldest clarifier of the three sludges which reflects why the initial CST measurements are similar to the long term measurements. The total solids, not shown, did not vary significantly during the course of this experiment.
Figure 47: Variation of primary sludge C CST and pH over three day test period
11 Appendix B – Mass Balance Calculations

For each experiment a mass balance was performed. The measurements and calculations are presented in Table 6, Table 7, Table 8, and Table 9 for dewatering biosludge-wood fine mixtures without a polymer. Values that were not obtained by direct measurements are marked with roman numerals.

Table 6: 50% wood fine dosage mass balance. All mass is recorded in grams.

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<tr>
<th>Run Number</th>
<th>Water in Slurry (g)</th>
<th>Biosolids in Slurry (g)</th>
<th>Wood Fines Added (g)</th>
<th>Total Mass in (g)</th>
<th>Biosolids in Filtrate (g)</th>
<th>Water in Filtrate (g)</th>
<th>Biosolids in Cake (IV)</th>
<th>Water in Cake (IV)</th>
<th>Total Mass Out (g)</th>
<th>Unaccounted Biosolids</th>
<th>Total Unaccounted Mass</th>
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<td>0% Moisture</td>
<td>1 298.5 3.9 1.9 0.0 245.3 189.6 0.8 17.2 1.5 1.9 211.0 32.7 1.6 34.3</td>
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Average: 0.66 17.1 1.4 40.8 1.6 42.4
Std. Deviation: 0.05 0.8 0.1 6.8 0.3 6.9

Table 7: 100% wood fine dosage mass balance. All mass is recorded in grams

<table>
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<tr>
<th>Run Number</th>
<th>Water in Slurry (g)</th>
<th>Biosolids in Slurry (g)</th>
<th>Wood Fines Added (g)</th>
<th>Total Mass in (g)</th>
<th>Biosolids in Filtrate (g)</th>
<th>Water in Filtrate (g)</th>
<th>Biosolids in Cake (IV)</th>
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</tbody>
</table>

Average: 0.66 23.9 1.7 36.9 1.1 38.0
Std. Deviation: 0.05 0.6 0.2 6.0 0.3 6.2
Table 8: 200% wood fine dosage mass balance. All mass is recorded in grams.

<table>
<thead>
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<th></th>
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</thead>
<tbody>
<tr>
<td>0% Moisture Content</td>
<td>1 239.5</td>
<td>3.9</td>
<td>7.7</td>
<td>0.0</td>
<td>251.1</td>
<td>174.7</td>
<td>0.6</td>
<td>38.3</td>
<td>2.4</td>
<td>7.7</td>
<td>223.7</td>
<td>26.5</td>
<td>0.9</td>
</tr>
<tr>
<td>35% Moisture Content</td>
<td>2 239.5</td>
<td>3.9</td>
<td>7.7</td>
<td>0.0</td>
<td>251.1</td>
<td>173.2</td>
<td>0.7</td>
<td>37.2</td>
<td>2.3</td>
<td>7.7</td>
<td>221.1</td>
<td>29.1</td>
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<td>64% Moisture Content</td>
<td>3 239.5</td>
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<td>7.7</td>
<td>0.0</td>
<td>251.1</td>
<td>173.9</td>
<td>0.6</td>
<td>38.5</td>
<td>2.6</td>
<td>7.7</td>
<td>223.3</td>
<td>27.1</td>
<td>0.7</td>
</tr>
<tr>
<td>78% Moisture Content</td>
<td>1 239.5</td>
<td>3.2</td>
<td>7.7</td>
<td>4.1</td>
<td>250.9</td>
<td>183.9</td>
<td>0.6</td>
<td>38.4</td>
<td>2.4</td>
<td>7.7</td>
<td>230.0</td>
<td>17.7</td>
<td>0.2</td>
</tr>
<tr>
<td>3 239.5</td>
<td>3.2</td>
<td>7.7</td>
<td>4.1</td>
<td>250.9</td>
<td>172.2</td>
<td>0.6</td>
<td>39.1</td>
<td>2.4</td>
<td>7.7</td>
<td>222.0</td>
<td>28.7</td>
<td>0.2</td>
<td>28.9</td>
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<tr>
<td>6 239.5</td>
<td>3.2</td>
<td>7.7</td>
<td>4.1</td>
<td>250.9</td>
<td>177.5</td>
<td>0.7</td>
<td>38.4</td>
<td>2.4</td>
<td>7.7</td>
<td>226.7</td>
<td>24.1</td>
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<td>Std. Deviation</td>
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<td>0.03</td>
<td>0.7</td>
<td>0.2</td>
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</tbody>
</table>

Table 9: 300% wood fine dosage mass balance. All mass is recorded in grams.

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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0% Moisture Content</td>
<td>1 239.5</td>
<td>3.9</td>
<td>11.6</td>
<td>0.0</td>
<td>255.0</td>
<td>157.3</td>
<td>0.6</td>
<td>48.6</td>
<td>2.6</td>
<td>11.6</td>
<td>220.7</td>
<td>33.6</td>
<td>0.7</td>
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<tr>
<td>35% Moisture Content</td>
<td>2 239.5</td>
<td>3.9</td>
<td>11.6</td>
<td>0.0</td>
<td>255.0</td>
<td>167.0</td>
<td>0.7</td>
<td>48.7</td>
<td>2.5</td>
<td>11.6</td>
<td>230.5</td>
<td>23.8</td>
<td>0.7</td>
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<tr>
<td>64% Moisture Content</td>
<td>3 239.5</td>
<td>3.9</td>
<td>11.6</td>
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<td>255.0</td>
<td>161.0</td>
<td>0.7</td>
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<td>223.4</td>
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<tr>
<td>78% Moisture Content</td>
<td>1 239.5</td>
<td>3.2</td>
<td>11.6</td>
<td>6.2</td>
<td>256.9</td>
<td>174.7</td>
<td>0.6</td>
<td>48.2</td>
<td>2.6</td>
<td>11.6</td>
<td>237.7</td>
<td>19.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2 239.5</td>
<td>3.2</td>
<td>11.6</td>
<td>6.2</td>
<td>256.9</td>
<td>171.4</td>
<td>0.6</td>
<td>52.0</td>
<td>2.4</td>
<td>11.6</td>
<td>237.0</td>
<td>19.7</td>
<td>0.2</td>
<td>19.9</td>
</tr>
<tr>
<td>3 239.5</td>
<td>3.2</td>
<td>11.6</td>
<td>6.2</td>
<td>256.9</td>
<td>160.7</td>
<td>0.6</td>
<td>50.8</td>
<td>2.3</td>
<td>11.6</td>
<td>231.0</td>
<td>25.6</td>
<td>0.3</td>
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<td>Average</td>
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<td></td>
<td></td>
<td>0.64</td>
<td>49.2</td>
<td>2.4</td>
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<tr>
<td>Std. Deviation</td>
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<td></td>
<td></td>
<td></td>
<td>0.03</td>
<td>1.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

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Mass Balance Table Notes:

I. The “Water in Slurry” is calculated from the total solid measurements made for the two biosludge batches used in these experiments. The first batch has an average density of 0.973 g/ml, the second batch has a density of 0.956 g/ml. The 5ml sample collected for the total solid measurements is 98.4% water by mass in the first batch and 98.7% water by mass in the second batch. The mass of water in the slurry is calculated by multiplying 250ml of sludge by the density and then the percentage of water for the batch it was sampled from.

II. The “Biosolids in Slurry” value was determined from the total solid measurement that was performed once for each batch of sludge. The first batch had a solids concentration of 15.4 g/l, and the second had a solids concentration of 12.7 g/l. Each 250ml sample has multiplied by the respective concentration to arrive at the amount of biosolids in the slurry. This value was assumed constant throughout the experiment for each batch.

III. For each experiment the total solids of the filtrate was measured in duplicate. The average density of the 5ml sample as well as the average mass fraction of water was determined for each experiment and used to calculate the mass of water in the filtrate.

IV. For each experiment the total solids of the filtrate was measured in duplicate, and this was used to determine the solids concentration of the filtrate. The average value from the duplicate measurements was multiplied by the volume of filtrate collected for each experiment to arrive at the total mass of biosolids in the filtrate. In this context “filtrate” means the water collected from both the gravity filtering and pressing operations.

V. For each experiment, the total mass of the cake was measured before and after drying in an oven at 103°C. The difference in the mass measurements is the amount of water that was in the filter cake. The amount of biosolids was determined by subtracting the amount of wood fines added from the total dry mass of the filter cake.

VI. The dry mass of the wood fines in the filter cake was assumed to be equal to the dry mass added to the slurry: 100% capture efficiency. This simplification is considered reasonable because the wood fines were larger than the openings in the filter media and could be collected by scraping the filter media after an experiment. Conversely, the biosludge solids were smaller than the filter media openings and became embedded in the fabric. Through visual observation, the biosludge solids constituted the majority of the particles that were retained on the filter media.
There are a few results from the mass balance that require further discussion. First, a large fraction of the starting mass is unaccounted for in each of the experiments (between 10-20%). Both the “Average Unaccounted Total Mass” and the standard deviation of this measurement are highest when the least amount of wood fines are used, the 50% dosage (Table 10). As the dosage of wood fines increases, both the total mass that is unaccountable and the standard deviation decrease. This is because the wood fines are improving the cake release properties and less material is being retained on the filter fabric. The changes in the “Biosolids in Cake” column for the four dosages confirm that less biosolids are being retained in the filter fabric as the dosage of wood fines in increased. At the 50% wood fine dosage the average calculated amount of biosolids in the cake is 1.4g. At a 300% wood fine dosage the average calculated amount of biosolids in the cake is 2.4g.

Table 10: Average unaccounted total mass and standard deviation of experiment mass balance

<table>
<thead>
<tr>
<th></th>
<th>50% Wood Fines</th>
<th>100% Wood Fines</th>
<th>200% Wood Fines</th>
<th>300% Wood Fines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Unaccounted</td>
<td>42.4</td>
<td>38.0</td>
<td>28.4</td>
<td>28.4</td>
</tr>
<tr>
<td>Total Mass [g]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>6.9</td>
<td>6.2</td>
<td>4.8</td>
<td>6.0</td>
</tr>
<tr>
<td>[g]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To determine where the unaccounted mass was and close the mass balance, the pieces of the experimental apparatus were weighed before and after two experiment replications. One replication, dewatering biosludge with no fines added, was chosen to represent the worst case, and the second replication, dewatering biosludge with a 200% dosage of biosludge, was chosen to represent a case with good cake release properties. The pieces of the experiment apparatus that were weighed and the changes in their weight are presented in Table 11.
Table 11: Amount of mass that adhered to the surfaces of the experiment apparatus.

<table>
<thead>
<tr>
<th>Collection Surface</th>
<th>Starting Weight [g]</th>
<th>Change in Weight [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Biosludge 200% Wood Fines</td>
</tr>
<tr>
<td>Beaker</td>
<td>184</td>
<td>1</td>
</tr>
<tr>
<td>Funnel</td>
<td>227</td>
<td>0</td>
</tr>
<tr>
<td>Gravity Filter</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Containment Ring</td>
<td>116</td>
<td>0</td>
</tr>
<tr>
<td>Belt Filters</td>
<td>386</td>
<td>23</td>
</tr>
<tr>
<td>Pressate Basin</td>
<td>38</td>
<td>1</td>
</tr>
<tr>
<td>Crown Press Channel</td>
<td>N/A</td>
<td>5-10</td>
</tr>
<tr>
<td>Total Mass</td>
<td>39 - 44</td>
<td>26 - 31</td>
</tr>
</tbody>
</table>

Less mass adhered to the surfaces of the experiment apparatus when the dosage of wood fines increased, which is in agreement with the results of the mass balance. The majority of the losses occurred within the crown press channel and on the filter media. The losses within the channel could not be measured so they were estimated based on the amount of water that it took to completely wet the channel surfaces. The decrease in the amount of mass adhering to the filter media is due to the wood fines improving the cake release properties. Moreover, the total mass measured adhering to the experiment apparatus is similar to the unaccounted total mass from the mass balance. The average total unaccounted mass for 50% wood fines and 200% wood fines (Table 10) is within the range of the total mass measured on the equipment apparatus for biosludge and 200% wood fines respectively (Table 11).

The second trend that the mass balance reveals is the amount of water in the cake does not depend on the moisture content of the wood fines, but rather on the dosage of wood fines used. Within each wood fine dosage, the standard deviation of the “Water in Cake” measurements is small, ranging between 0.6-1.3g, despite having the moisture content of the wood fines increased from 0% to 78%. However, as the dosage of wood fines is increased from 50% to 300% the average of the “Water in Cake” measurements increases (17.1g, 23.9g, 38.2g, and 48.9g for 50%, 100%, 200%, and 300% wood fine dosages respectively).

Third, the average “Biosolids in Filtrate” is not statistically different for all of the wood fine dosages. Therefore, the wood fines do not help capture more biosludge particles regardless of
the dosage used or the moisture content of the wood fines. However, the filtrate total solids measurements decreased as the moisture content of the wood fines increased (Section 5.5.2). At higher moisture content the wood fines absorb less water from the biosludge because they are closer to their moisture saturation point, thus more filtrate was collected. Since the filtrate total solids measurement is a concentration (grams of solid per volume), and the amount of solids in the filtrate does not change, collecting more filtrate will decrease the filtrate total solids measurement.

Fourth, the water in the cake can be predicted within 1g on average for the 50% and 100% wood fine dosage experiments by using the following equation:

\[
Water\ in\ Cake = (\text{dry biosolids})(WC_{BS}) + (\text{dry wood fines})(WC_{WF})
\]  

where all the values are measured in grams, and \(WC_{BS} = 8g/g\) biosludge and \(WC_{WF} = 2.8g/g\) wood fines. \(WC_{BS}\) and \(WC_{WF}\) are determined by dewatering a sample of biosludge and a separate sample of wood fines that have been soaked in water overnight, and then measuring the amount of water per grams dry mass in the filter cake. Being able to use the above equation to predict the amount of water in the cake indicates that there is little interaction between the wood fines and the biosludge particles, and that they are dewatering independently of one another. The average difference between the water content predicted by the above equation and the measured water content increases for the 200% and 300% dosages to 1.5g and 2g respectively. The standard deviation of the measurements also increases. This increase is still small, but suggests that the particles may be interacting with one another and changing the amount water that they absorb.

Lastly, water accounts for the majority of the mass and the variability in the “Total Unaccounted Mass” measurements. This is not surprising because water is also the largest constituent by mass in the slurry. The water in the unaccounted mass exists in different forms: as free water on the surfaces of the filter media and equipment apparatus, as absorbed water in the biosludge particles, and absorbed water in any wood fine particles.

A similar mass balance was performed for the experiments that compared the performance of primary sludge fibres to wood fines. Table 12 presents the results for the experiments that were conducted without a polymer, and Table 13 presents the results for the experiments that used a
polymer. Values that were not obtained by direct measurements are marked with roman numerals.

Table 12: Mass balance of wood fines and primary sludge comparison – no polymer. All mass is recorded in grams.

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Water in Slurry (I)</th>
<th>Biosolids in Slurry (II)</th>
<th>Physical Conditioner Added</th>
<th>Total Mass In (III)</th>
<th>Biosolids in Filtrate (IV)</th>
<th>Water in Cake (V)</th>
<th>Biosolids in Cake (VI)</th>
<th>Physical Conditioner in Cake (V, VI)</th>
<th>Total Mass Out</th>
<th>Unaccounted Water</th>
<th>Unaccounted Biosolids</th>
<th>Total Unaccounted Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>238.0</td>
<td>3.9</td>
<td>0.0</td>
<td>257.4</td>
<td>198.4</td>
<td>0.3</td>
<td>14.9</td>
<td>2.6</td>
<td>216.2</td>
<td>40.2</td>
<td>1.0</td>
<td>41.2</td>
</tr>
<tr>
<td>2</td>
<td>238.0</td>
<td>3.9</td>
<td>0.0</td>
<td>257.4</td>
<td>199.6</td>
<td>0.4</td>
<td>16.2</td>
<td>2.9</td>
<td>219.1</td>
<td>37.7</td>
<td>0.6</td>
<td>38.3</td>
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<tr>
<td>3</td>
<td>238.0</td>
<td>3.9</td>
<td>0.0</td>
<td>257.4</td>
<td>205.3</td>
<td>0.4</td>
<td>15.8</td>
<td>2.8</td>
<td>224.3</td>
<td>32.4</td>
<td>0.7</td>
<td>33.1</td>
</tr>
</tbody>
</table>

Table 13: Mass balance of wood fines and primary sludge comparison – with polymer. All mass is recorded in grams.

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Water in Slurry (I)</th>
<th>Biosolids in Slurry (II)</th>
<th>Physical Conditioner Added</th>
<th>Water in Polymer</th>
<th>Total Mass In (III)</th>
<th>Biosolids in Filtrate (IV)</th>
<th>Water in Cake (V)</th>
<th>Biosolids in Cake (VI)</th>
<th>Physical Conditioner in Cake (V, VI)</th>
<th>Total Mass Out</th>
<th>Unaccounted Water</th>
<th>Unaccounted Biosolids</th>
<th>Total Unaccounted Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>238.0</td>
<td>3.9</td>
<td>3.8</td>
<td>15.5</td>
<td>261.2</td>
<td>194.9</td>
<td>0.4</td>
<td>22.9</td>
<td>3.9</td>
<td>225.0</td>
<td>35.7</td>
<td>0.6</td>
<td>36.2</td>
</tr>
<tr>
<td>2</td>
<td>238.0</td>
<td>3.9</td>
<td>3.8</td>
<td>15.5</td>
<td>261.2</td>
<td>196.7</td>
<td>0.4</td>
<td>23.0</td>
<td>3.9</td>
<td>227.2</td>
<td>33.5</td>
<td>0.5</td>
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<tr>
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<td>3.8</td>
<td>15.5</td>
<td>261.2</td>
<td>198.2</td>
<td>0.4</td>
<td>24.1</td>
<td>3.9</td>
<td>229.6</td>
<td>31.2</td>
<td>0.5</td>
<td>31.6</td>
</tr>
</tbody>
</table>
Mass Balance Table Notes:

I. The “Water in Slurry” is calculated from the total solid measurements made for the two biosludge batches used in these experiments. The first batch has an average density of 0.964 g/ml, the second batch has a density of 0.967 g/ml. The 5ml sample collected for the total solid measurements is 98.2% water by mass in the first batch and 98.4% water by mass in the second batch. The mass of water in the slurry is calculated by multiplying 250ml of sludge by the density and then the percentage of water for the batch it was sampled from.

II. The “Biosolids in Slurry” value was determined from the total solid measurement that was performed once for each batch of sludge. The first batch had a solids concentration of 17.3 g/l, and the second had a solids concentration of 15.3 g/l. Each 250ml sample has multiplied by the respective concentration to arrive at the amount of biosolids in the slurry. This value was assumed constant throughout the experiment for each batch.

III. For each experiment the total solids of the filtrate was measured in duplicate. The average density of the 5ml sample as well as the average mass fraction of water was determined for each experiment and used to calculate the mass of water in the filtrate.

IV. For each experiment the total solids of the filtrate was measured in duplicate, and this was used to determine the solids concentration of the filtrate. The average value from the duplicate measurements was multiplied by the volume of filtrate collected for each experiment to arrive at the total mass of biosolids in the filtrate. In this context “filtrate” means the water collected from both the gravity filtering and pressing operations.

V. For each experiment, the total mass of the cake was measured before and after drying in an oven at 103°C. The difference in the mass measurements is the amount of water that was in the filter cake. The amount of biosolids was determined by subtracting the amount of physical conditioner added from the total dry mass of the filter cake.

VI. The dry mass of the physical conditioner in the filter cake was assumed to be equal to the dry mass added to the slurry: 100% capture efficiency. This simplification is considered reasonable for the wood fines because the wood fines were larger than the openings in the filter media and could be collected by scrapping the filter media after an experiment. The primary sludge fibers are also larger than the filter media openings, but due to their much smaller size, could not be entirely removed from the filter media. This is more of a problem when a polymer was not used (larger error) than when one was used because the combination of the primary sludge fibres and the polymer released the filter cake with minimal residues of any kind. The biosludge solids were smaller than the filter media openings and became embedded in the fabric. Through visual observation, the biosludge solids constituted the majority of the particles that were retained on the filter media.
From the primary sludge comparison experiments that were conducted without a polymer, the most significant result is the differences in the biosludge particle capture between the three mixtures. The biosludge and biosludge-wood fine mixtures had approximately the same amount of biosolids in the filtrate and filter cake, but the biosludge-primary sludge mixture had 50% fewer biosolids in the filtrate and over 5 times more biosolids in the filter cake. This is due to the primary fibres forming a good filter cake during gravity filtration, which captured more biosludge particles, and acting as a filter aid by improving the filter cake handling properties, which allowed for a clean release from the filter media.

The “Total Unaccounted Mass” is higher in this experiment than in the initial wood fine experiments. This can be partly explained by the higher amount of “Unaccounted Biosolids”, which are comprised with a large amount of water. Less filtrate is collected overall as well. This is thought to be partly due to differences in the sludge used.

When a polymer was used the “Total Unaccounted Mass” was lowered to be between 30-40g for all four mixtures. This means that the polymer alone provides a substantial benefit to increasing the capture efficiency of biosludge solids. There is no significant difference between the biosolids within the filtrate between the four mixtures, but there is a slight increase in the amount of biosludge solids in the filter cake when a physical conditioner is used. This is partly explained by better cake handling properties because every mixture that had a physical conditioner had fewer biosludge particles lodged within the filter media.

The biosludge mixtures that had physical conditioners also had more water in the filter cake, and there was more water when higher dosages were used. This is likely due to the moisture absorption capacity of the physical conditioners.