KENAF AS A POLYELECTROLYTE SUBSTITUTE
IN
SLUDGE DEWATERING

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ABSTRACT

The objective of this research was to investigate an alternative to polyelectrolytes for sludge conditioning prior to mechanical dewatering. Polyelectrolytes (polymers) did not result in a final cake with a solids content sufficiently high for the sludge to be beneficially reused, such as in incineration. Agricultural fibers (kenaf) were used to increase the structural strength and permeability of sludge samples in order to improve the final solids content of cakes. Kenaf had intrinsic energy content (16.3 MJ/kg), and provided the energy of sludge cakes, which could be used as energy sources for incineration.

The laboratory experiments showed that conditioning with a kenaf-polymer blend prior to filtration and centrifugation tests produced a higher solids content than the tests with kenaf or polymer only. Furthermore, the blend enhanced the dewatering rates of filtration and centrifugation as compared to single conditioner treatments. The blended conditioning appeared better because the high solids content cakes with useful energy content at favorable dewatering rates could be produced, while the other treatments could not produce cakes with all these properties.

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CHAPTER 1

INTRODUCTION

The volume of municipal wastewater generated increases in proportion to population growth. Wastewater treatment generates high solid-fraction slurries that are disposed of into the environment. This slurry is semisolid, odious, difficult to manage, and sometimes dangerous. It is commonly called *sludge* or *biosolid.*

Municipal wastewater sludge disposal is an area of ongoing concern. The increasing volume of sludge requires an enormous land area for landfill-type disposal. This disposal approach presents a critical problem in wastewater treatment, and re-use methods are always preferred.

In any approach, solid-liquid separation (SLS) is needed to reduce the volume of sludge and to render sludge useful for other purposes. The two principal approaches to volume reduction are: (1) sludge thickening and (2) separations with filters, belt presses, and centrifuges. These approaches result in increased solids concentration and total volume reduction, but differ in solid concentration degree.

Sludge thickening produces less than 15 % (v/v) solids after treatment. Such a sludge is still pumpable by conventional means and has most of the characteristics of a liquid. However, filters, presses, and centrifuges produce concentrations of sludge solids exceeding 15 % by volume, and this sludge generally behaves more like a solid.

Typically wastewater treatment plant operators attempt to reduce the volume of sludge before final disposal because the volume of sludge directly impacts the disposal cost. The typical cost of sludge handling systems in terms of capital and operating costs ranges from one-fourth to one-half of the total cost of wastewater treatment (Karr and Keinath, 1978).

1-1 SOLID-LIQUID SEPARATION PROCESSES

1-1-1 Sludge Thickening

Sludge thickening methods include gravity thickening, floatation, and screening as typical processes. These methods exploit either density differences or size characteristics of the solid materials.

Gravity thickening separates a feed slurry into an underflow slurry of higher solids concentration and an overflow of substantially clear liquid. A density difference between the solids and the liquid is necessary for success.

Floatation uses air bubbles supplied to the suspension. The solids attach to the bubbles, and are transported to the surface and scraped off. Flotation is divided into dispersed air, dissolved air and electrolytic flotation, depending on the way the gas bubbles are generated. Flotation is in common use in the mineral separation field and, is recognized as an effective means of solid-liquid separation in other applications such as papermaking, refineries or sewage treatment.

Screening passes the slurry through a medium that by size exclusion separates solids from liquid. Although screening is usually used for classification of solids, screens are also useful for dewatering of coarse or highly flocculated suspensions. Vibration or some other type of motion is often employed to make sure that sooner or later all the materials are introduced to the screen apertures and that the apertures do not block.

1-1-2 Sludge Dewatering

Sludge dewatering methods include drying beds, lagoons, vacuum filters, pressure filters, centrifuges and belt presses. These methods also exploit density and size characteristics of the solid materials but to a much higher degree than thickening methods. Drying exploits the phase change of the liquid during evaporation.

Drying beds were historically the first method of sludge dewatering. The only reasonable means of drying is the classical sand-drying bed that uses solar energy as a heat source. The sand covers a tile field and the sludge is spread on the sand, usually about eight inches deep. During the first dew days, the primary means of dewatering is filtration through the sand. When drainage stops, the major liquid removal mechanism becomes evaporation. Typically, sludges lose enough liquid to crack, and this cracking promotes further drying. In 30 to 60 days, municipal sludges are typically at solids concentrations of 30 to 40 % by mass. Covered beds yield even drier solids. Land costs generally limit the use of drying beds to small communities.

A lagoon consisting of nothing more than a hole-in-the-ground is often employed as an expeditious and low cost means of sludge dewatering. Sludge is pumped into the lagoon at varying depths, and is allowed to evaporate. Usually, there is no underdrain system for drainage. The process is slow and requires large lagoon volume. Odor problems are typical.

Vacuum filtration techniques employ a porous filter medium to support the filter deposit. Unlike other filter forms, vacuum filtration employs a relatively low driving force. The disadvantages come from the limitation in driving force which may lead to low filtration rates and higher than acceptable cake moistures. For compressible cakes, higher pressures may lead to high cake resistance and medium resistance, a factor often encountered in the use of filter presses. The design problems encountered for both batch and continuous vacuum filters tend to be less difficult to overcome than for filters which operate at high pressures or at high speeds of rotation.

In vacuum filtration, chemicals used to condition the sludge and thus make it easier to filter are combined with the feed sludge and placed in a trough that sits underneath a large rotating drum. This drum is covered with a permeable fabric or other material. A vacuum is drawn inside the drum, and water is sucked through the fabric into vacuum lines inside the drum and pumped out as the filtrate. The solids that cannot get through the fabric are caught on the surface of the drum and removed as the filter cake.

Pressure filtration differs from vacuum filtration in that the liquid is forced through the filter medium by a positive pressure instead of a vacuum. The driving force for filtration in pressure filters is usually the liquid pressure developed by pumping or by the force of gas pressure in the suspension feed vessel. Alternatively, the liquid may be squeezed through and out of the cake by the mechanical action of an inflatable membrane, a piston or a porous medium pressed on top of the cake.

Pressure filtration is defined as any means of surface filtration where the liquid is driven through the medium by either hydraulic or mechanical pressure. The solids are deposited on top of the filter medium as in all surface filters. Most conventional pressure filters are operated as batches, i.e., the whole of the filter medium surface in each unit is going through a cyclic process of cake formation followed by cake washing or dewatering and cake removal. This leads to discontinuous solids discharge from the filter, usually taking place during that part of the cycle when the filter is taken off pressure and is opened to the atmosphere. (Svarovsky, 1990)

In 1902 the first centrifugal dewatering of sludge was tried. Although the machine operation was rather good, the electrical cost was too high and the experiment was discontinued. The combination of improved techniques in machining and especially in the production of organic polyelectrolytes (polymers) for sludge conditioning finally made centrifugation a feasible and attractive alternative to vacuum filtration.

There are three typical groups of centrifuge types for solid-liquid separation: sedimentation centrifuges, centrifugal filters, and liquid-liquid separators. This catagorization arises because centrifuges are employed in filtration and sedimentation of solid-liquid suspensions and emulsions. Thus centrifuges are available for most separation problems and frequently may compete with filters. In principle, all types of centrifuges are more expensive than corresponding filters with some exceptions, so that the selection may commonly be influenced by economic and operational considerations.

An essential advantage of centrifugal separations is that a centrifuge needs less space than a corresponding filter of the same capacity. The solid-bowl centrifuges (or the decanter) are frequently used for wastewater treatment. This machine has the ability of dewatering, or at least separation, of any solid from any liquid, as long as the solids are heavier than the liquid. Sludge water is pumped through a central pipe into a rotating bowl and because of centrifugal force hugs the inside walls of the bowl. The heavier solids will flow to the wall and the lighter liquid will remain pooled on top. It is necessary to remove the sludge from the bowl, this process is accomplished by the scroll, or screw conveyor.

1-2 ULTIMATE DISPOSAL OF SLUDGES

Land application of sludges has been practiced successfully for a long time. The interest in land application of sludge has increased in recent years. In the land application of stabilized municipal wastewater sludge the spreading of sludge on or just below the soil surface is used. Land application is currently the most widely employed sludge use and disposal method among small and medium sized treatment plants in the United States.

For further sludge treatment, sludge may be applied to agricultural land, forest land, disturbed land, and dedicated land disposal sites. Sunlight, soil microorganisms, and desiccation combine to destroy pathogens and many toxic organics found in sludge. Sludge acts as a soil conditioner to facilitate nutrient transport, increase water retention, and improve soil tillage. It also serves as a partial replacement for expensive chemical fertilizers.

If a suitable site is available, a sanitary landfill can be used for disposal of sludge. Stabilization may be required depending on state or local regulations. Dewatering of sludge is usually needed to reduce the volume to be transported and to control the generation of leachate from the landfill. Solids concentration is an important factor in determining whether a landfill is good for sludge disposal or not.

In selecting a land disposal site, several considerations are required. At first environmentally sensitive areas such as wetlands, flood plains, recharge zones for aquifers, and habitats for endangered species should be considered. Runoff control to surface water, groundwater protection and air pollution from dust, particulates and odors should be also considered. Land application has some benefits; however it also has several problems such as odor, transferring pathogens, transmittal of toxins and cost of land and transportation.

Oceans and large lakes provide extensive assimilation capacity and are used for wastewater disposal by many communities. The wastewater is typically carried to an offshore discharge point by a pipe laid on or buried in the ocean floor, or by a tunnel. The discharge can be through a single-port or multiport-outfall structure.

In coastal waters, stratification may prevent the mixing of sludge within the main body of water. One of the problems of ocean disposal is that floating materials are swept back to the shore discourage recreational fishing and swimming. Another problem is that large slugs of sludge deplete the oxygen within the disposal plume and cause loss or relocation of marine life (Vesilind, 1979). The accumulation of deposits on the bottom of the ocean from sludge disposal can destroy the submarine benthic community by burial and excess oxygen demand.

Thermal treatment is another method for sludge dewatering and stabilization. It is normally unnecessary to stabilize sludge before incineration. In fact, such practice may be detrimental because stabilization decreases the volatile content of the sludge and consequently increases the requirement for an auxiliary fuel. An exception is the use of heat treatment ahead of incineration. Heat treated sludges are dewatered extremely well, making the sludge autocombustible. Sludges may be subjected to thermal treatment separately or in combination with municipal solid wastes.

Although most wastewater sludges are comprised of organic materials, they will sustain combustion only if sufficient quantities of water have been removed. The removal of this water is expensive and difficult. In addition to the moisture content, the value of sludge as an heat material also depends on the energy content. The amount of auxiliary fuel for incineration will define the efficiency of the combustion process.

1-3 PROBLEM STATEMENT

Usually raw sludge is treated with chemicals (polyelectrolytes) to generate large flocs of biosolids to enhance subsequent dewatering steps. While the polymers are helpful, they are expensive and dosage and process controls are still poorly understood. A significant problem in polymer addition is dosage control-insufficient polymer degrades performance; overdosing the polymer increases costs. The mechanism of polymer action during the conditioning of sludge appears to be that of increasing the effective particle size which increases the filterability. Anecdotal evidence exists that sludges high in fibers have enhanced dewatering properties, and nations where fiber intake is high tend to report drier sludge cakes using commercial dewatering methods.

Fibers fed into sludge will give more porosity between the particles of sludge, improving the filtration rate. Filtration rate, water content of cakes, and the capacity of filtrate recovery are all the important factors governing the dewaterability.

Organic fibers can add a significant amount of energy value to the sludge cake. Although energy recovery is not considered re-use in the United States, in other energy-poor nations the combustion of a waste material as a fuel is attractive and encouraged. It also reduces the land area required for landfill-type disposal of wastewater sludge. Furthermore the ash from combustion can be used as a construction material.

This line of evidence suggests that certain waste or virgin fibers may be able to provide similar performance as polymers. Unknown is whether fiber dosage must be as carefully controlled as polymer content. Although anecdotal evidence suggests fibers can substitute for polymers as a dewatering aid, there is no systematic study of the feasibility of fiber substitution to enhance sludge dewatering. Therefore, this research will provide a starting point for testing the feasibility of fiber substitution for polymer. The fiber used is kenaf, a high-cellulose content organic fiber.

1-4 RESEACH OBJECTIVES

The objectives of this research are to compare the performance of kenaf to polymer for dewatering enhancement and to determine the potential for cake incineration.

The general research approach is listed below:

1. Find optimal conditions for polymer and kenaf addition for reducing water contents of filter and centrifuge cakes. Conditioner dosage, kenaf size, and polymer concentration are the principal independent variables.

2. Determine optimal conditions for increasing the energy contents of cakes for incineration with less auxiliary fuel or without fuel.

3. Determine conditions that produce low water content of cakes and the high energy content.

4. Compare the results of kenaf with those of polymer and compare filtration with centrifugation.

CHAPTER 2

LITERATURE REVIEW

2-1 FILTRATION

Filtration is one of the most general areas of solid-liquid separation that is frequently encountered in industrial processes. The liquid pressure is usually used as the driving force for filtration in pressure filters. The pressure is developed by pumping or by the force of gas pressure in the suspension feed vessel. In addition, the liquid may be squeezed through and out of the cake by the mechanical action of an inflatable membrane, a piston or a porous medium pressed on top of the cake. Pressure filtration is defined as any means of surface filtration where the liquid is driven through the medium by either hydraulic or mechanical pressure.

Filtration may be defined as the separation of solids from liquids by passing a suspension through a permeable medium which retains the particles. The most important feature of the pressure filters, which use hydraulic pressure to drive the process, is that they can generate a pressure drop across the medium of more than one bar, which is the theoretical limit of vacuum filters. Filtration operations may be classified in several ways according to the method of particle deposition, driving force, pumping mechanism, and continuity of operation. Filtration operations can be divided into three categories: depth, cake, and cross-flow filtration. In this research cake filtration is studied.

In cake filtration the solid material accumulates on the surface of the medium, so that, after a short initial period, filtration is through the bed of deposited solids. This process will continue until the pressure drop across the cake exceeds the maximum permitted by economic or technical considerations or until the space available is filled. This method of filtration is the most widely employed in the process industries and is very well suited to the filtration of concentrated suspensions and the recovery of large quantities of solid. The most important factor in cake filtration is the permeability or resistance of the filter cake, and this may be controlled, to some extent, by altering the particle-size distribution of the material, sometimes by adding another solid to it, and also by altering the state of aggregation of the solids.

In a cake filter, the filter medium has a relatively low initial pressure drop and particles equal to or greater than the size of the openings wedge into the openings and create smaller passages which then remove even smaller particles from the fluid. A filter cake is thus formed, which in turn functions as a medium for the filtration of subsequent input suspension. In order to prevent blinding of the medium, filter aids are used as a precoat which forms an initial layer on the medium. Some penetration of fine solids into the precoat or the medium itself is often inevitable.

Cake filters are usually used for suspensions with higher concentrations of solids, above 1 % by volume, because of the blinding of the medium that occurs in the filtration of dilute suspensions. This blinding can sometimes be avoided by an artificial increase of the input concentration, in particular by adding a filter aid as a ‘body feed’; as filter aids are very porous, their presence in the cake improves permeability and often makes cake filtration of dilute and generally difficult slurries possible.

Filter cakes can be classified according to the variation of permeability and porosity with pressure increase. If the values of permeability and porosity change as the pressure difference is increased, then the cake is termed “compressible.” Usually, the permeability and porosity decrease with increasing pressure, and the average porosity is expected to decrease during the course of filtration. If these parameters remain constant throughout the course of filtration, the cake is called “incompressible.”

2-1-1 Studies of Filtration Dewatering

There have been some relatively recent studies about sludge dewatering by means of pressure filtration. Many pressure filtration tests were conducted using compressed air or some other gas. In most of the filtration dewatering tests, filtration aids (conditioners) are mixed with the primary or secondary sewage sludge before filtration.

Smollen and Kafaar (1997) used polymer and a pyrolysed domestic refuse(char) as conditioners. The experiments tested four different treatments: no conditioners, polymer only, char only, and polymer plus char. When they used an admixture of char and polymer conditioner, they observed cake solids concentrations between 30 and 40 %. This concentration was double that of polymer alone.

Shin and Lee (1996) studied dewatering characteristics of primary sewage sludge using bituminous coal as a filter aid. In their study moisture content and specific resistance of the filter cake were measured under various pressure, polymer dosages, and coal dosages. They found that the moisture content in the filter cake was reduced by 20 % when bituminous coal alone was added into the primary sludge. With polymer additions they also found measurable reduction of cake moisture content, but polymer dosage above 5 % of dry solid content, produced no additional decrease in moisture content. This result strongly supports the general knowledge that polymer overdosage has no process benefit.

Park and Kwon (1988) conducted an experimental study on the dewaterability improvement and the waste-heat recovery of sewage sludge by fine coal addition. They found that the addition of fine coal reduced the specific resistance and moisture content of filter cakes. They also found that the addition of fine coal increased the compressibility of sludge and speculated that the fine coal behaved as an adsorbent, which contributed to a higher quality filtrate.

Karr and Keinath (1978) investigated the role of particle size on sludge dewaterability. They reported that there were many factors influencing sludge dewatering characteristics: cellulose content, pH, particle charge, organic content, filtrate viscosity, solids concentration, conditioning, compressibility and particle size. They concluded from a detailed examination of the literature that the single factor which most influenced sludge dewaterability was particle size.

2-1-2 Fundamental Equations for Cake Filtration

The process of cake filtration involves the separation of fine solid particles, usually of such a size that they will not easily settle, from the liquid in which they are dispersed by collecting the solid particles on the surface of a medium, which is permeable only to the liquid. As the process continues, additional particles are collected on the surface of the initial layer of solids, thereby building up a cake.

At any instant of time during the build-up of the cake, the liquid will be flowing through solids already deposited. The flow rate through a filter cake is governed by the classical Darcy Law Equation (Harvey et al., 1988) in spatial coordinates as

$$\frac{dp_L}{dx} = \frac{-dp_s}{dx} = \frac{\mu q}{K} \qquad (2\text{-}1\text{-}1)$$

or in mass coordinates as

$$\frac{dp_L}{dw} = \frac{-dp_s}{dw} = \mu q \alpha \tag{2-1-2}$$

which relates the local values for the hydraulic pressure gradient (dp_L/dx) or the drag pressure gradient (dp_s/dx) to the local permeability (K), where q is the superficial filtrate velocity and μ is the filtrate viscosity. The mass coordinate w is the mass of dry cake per unit area to distance x, and α is the local filtration-specific resistance.

Integrating Equation (2-1-2) over the cake thickness at any given time and expressing the result in resistance form gives

$$\frac{p}{\mu q} = \alpha_{av} w_c + R_m, \tag{2-1-3}$$

where p is the applied pressure, α_{av} the average specific cake resistance, and R_m the resistance of the filter medium.

Almost all filter cakes show some changes in permeability or porosity as filtration pressures are altered. Porosity differences are most easily seen as changes in moisture content of the cake. Clearly in a completely incompressible cake, it is impossible to reduce the moisture content by increasing the filtration pressure.

The flow rate per unit area q relates to the pressure drop Δp, the mass of cake deposited w and other parameters,

$$q = \frac{\Delta p}{\alpha_{av} \mu\, w + \mu\, R_m}. \qquad (2\text{-}1\text{-}4)$$

In Equation (2-1-4) the medium resistance R_m is assumed to be a constant and the cake resistance R_c is specific resistance α times the mass of cake deposited per unit area. The pressure drop Δp may be constant or variable with time depending on the characteristics of the pump used or on the driving force applied. And the face area of the medium is usually constant. The liquid viscosity μ is constant provided that the temperature remains constant during the filtration cycle.

A mass balance on a per unit filter area basis (slurry mass = cake mass + filtrate mass) gives the mass of cake deposited per unit area w is a function of time in batch filtration processes. It can be related to the cumulative volume of filtrate per unit area v filtered in time t by

$$\frac{w}{s} = \frac{w_c}{s_c} + \rho v, \qquad (2\text{-}1\text{-}5)$$

where s is the mass fraction solids in slurry, s_c is average mass fraction solids in cake, and ρ is liquid density.

The general filtration Equation (2-1-4) after substitution of *w(t)* from Equation (2-1-5) becomes

$$q = \frac{\Delta p}{\alpha \, \mu \, c \, v + \mu \, R}. \tag{2-1-6}$$

The total flow volume is an integral function of the flow rate,

$$q = \frac{dv}{dt}. \tag{2-1-7}$$

Equation (2-1-6) can be rewritten in reciprocal form, which is more convenient for further treatment,

$$\frac{dt}{dv} = \alpha \, \mu \, c \frac{v}{\Delta p} + \frac{\mu \, R}{\Delta p}. \tag{2-1-8}$$

2-1-3 Filter Aids

Filter aids are employed in two ways in sludge dewatering to improve filterability. One is using filter aids as precoats on filter medium surfaces. The precoat bridges large openings in screens and form permeable porous surfaces. If a cake is deposited on the precoat, the filter aid protects the supporting medium and increases the ease with which the cake can be removed.

The second role of filter aids is to increase the permeability of the cakes which leads to higher process rates when it is added to slurries. Filter aids are frequently employed as both precoats and admix in the same filtration operation (Tiller and Zhou, 1994).

To be effective as a filter aid, a material should have porosity close to 90 % and pores of the appropriate size to provide the desired clarity. Irregularly shaped particles present in diatomaceous earth, expanded perlite, and fibrous cellulosic materials are good filter aids.

In filtration, a high rate of solid-liquid separation is desired. However, there are some problems in filtration; slow filtration rate, rapid medium blinding, or unsatisfactory filtrate clarity. Filterability of slurries may be improved by either chemical or physical methods. Using filter aids, which are granular or fibrous materials capable of forming highly permeable filter cakes, can improve the filterability. A number of materials can be used as filter aids, including diatomaceous earth, expanded perlite, and cellulose (fibers). They are used as precoat or as admix. When filter aids are used as precoat, a layer of medium is formed which protects the basic medium of the system and prevents the escape of small particles into the filtrate. When using filter aids as the admix, they trap the difficult-to-filter material in the pores of the precoat.

Materials which make particles easier to filter, such as flocculants, may be thought of as preconditioning agents and are not filter aids. Filter aids are effective to the extent that they can provide a high degree of particle retention, they can hold a large quantity of particles and provide high rates of flow. The principal properties that enable them to do this are permeability, pore size of filter aid cakes, and incompressibility.

The major purposes of using filter aids as admixes lie in their ability to reduce filtration specific resistance and to increase cake porosity. The cake permeability increases as the cake porosity increases. Therefore, as filter aid is added, the additional bulk offsets the decreased specific resistance. The total cake resistance reaches a minimum and then rises, the flow rate reaches a maximum and then decreases.

However, having selected the grade of filter aids for precoat and body feed, it is necessary to determine the amount of body feed addition. This depends on the amount and type of suspended solids and the desired cycle length.

Smith (1990) showed that 25 % by weight of body feed on the weight of the solids began to be effective in lengthening the filter cycle, with the maximum effective amount of body feed usually being equal to two times the weight of suspended solids for incompressible suspended solids. For highly compressible solids, the amount of body feed addition may be one to eight times the weight of suspended solids.

Coagulants and flocculants are also used to aggregate solids to form flocs. Flocculated slurries have much higher filtrate flow rate. However, the resulting cakes normally have a higher liquid content than those formed by dispersed slurries. In as much as high filtrate flow rate and low cake liquid content are the goals of solid-liquid separation, a compromise must be reached between these two variables.

Tiller and Zhou (1994) studied the use of kenaf (agricultural fibers) as aids in solid-liquid separation. These agricultural fibers are derived from annual crops. Kenaf is a fast growing annual plant consisting of an outer fibrous bark and an inner woody core. Kenaf is used not only promising as solid-liquid separation aids but also as a substitute for wood pulp in paper manufacture. It is also useful for absorbing oil and has a potential for coalescing oil and serving as a combustible filter aid. They also observed that kenaf had the ability to increase cake permeability and to reduce turbidity when used as a filter aid.

2-2 CENTRIFUGAL FILTRATION

The centrifugal dewatering of waste sludge has been practiced for many years. Recently, there have been significant improvements in flocculants, notably the development of very high molecular weight organic polyelectrolytes. These flocculants produce durable flocs that are not readily broken up by the shearing forces in a centrifuge and that often reform if broken up.

The common feature of all filter centrifuges is a rotating basket equipped with a filter medium. Although this is a rather simple characteristic, its actual application has led to an astounding variety of different designs. Therefore, the theoretical treatment of the filtration process will be limited to cylindrical baskets. Conical and other possible shapes can be dealt with by the same approach.

To simplify the theoretical treatment, the filtration resistance of the filter medium is considered negligible as compared to the filtration resistance of the cake. The introductory treatment to follow will assume the filter cake to be homogeneous. In most practical cases, centrifugal sedimentation proceeds at a much faster rate than centrifugal filtration so that after filling the basket and some transient settling phenomena the process can be characterized by a filter cake submerged in an annulus of clear liquid. This situation is shown schematically in Figure 2-1.

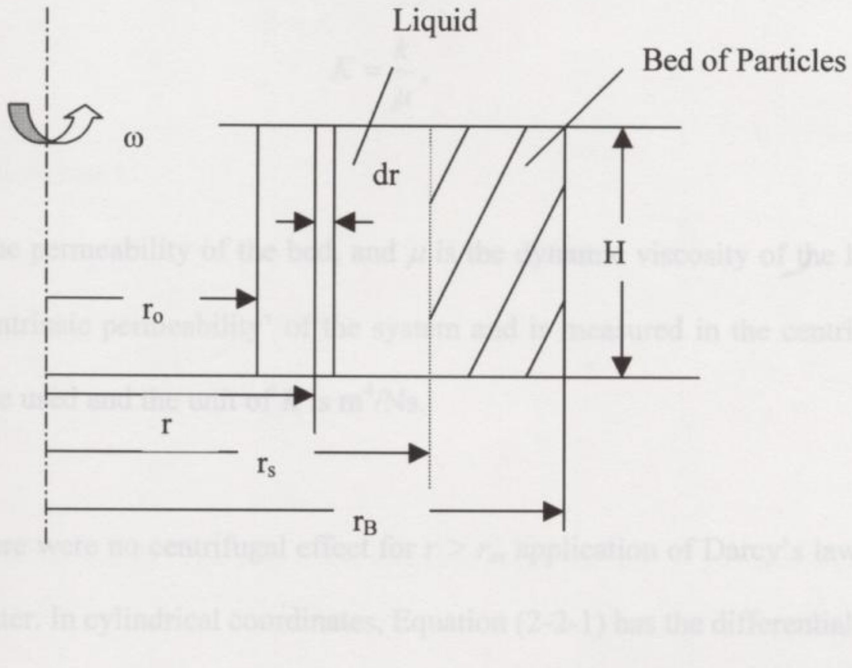

Figure 2-1 Geometry of Centrifugal Filtration

The fundamental filtration law as formulated by Darcy states that the flow of a liquid through a porous bed of particles requires a pressure difference across the bed; the original form of the equation for the linear case is

$$q = \frac{K \, \Delta p}{L}, \tag{2-2-1}$$

where q is the flow rate of liquid passing through the cake per unit area, K is a proportionality constant, Δp is the pressure drop across the cake in the direction of the flow, and L is the thickness of the cake.

The constant K is

$$K = \frac{k}{\mu}, \tag{2-2-2}$$

where k is the permeability of the bed, and μ is the dynamic viscosity of the liquid. K is called the 'intrinsic permeability' of the system and is measured in the centrifugal field which will be used and the unit of K is m^4/Ns.

If there were no centrifugal effect for $r > r_s$, application of Darcy's law would be a simple matter. In cylindrical coordinates, Equation (2-2-1) has the differential form,

$$\frac{dP}{dr} = -\left(\frac{q}{2\pi\, K\, H}\right)\cdot\left(\frac{1}{r}\right). \qquad (2\text{-}2\text{-}3)$$

With the previous restriction to pressures above the ambient pressure, the boundary conditions are as follows:

(a) $P = 0$ at $r = r_B$,

(b) $P = P_s$ at $r = r_s$.

From these boundary conditions the following equations are developed. The pressure at a radius r is

$$P(r) = \frac{q}{2\,\pi\, K\, W}\,\ln\left(\frac{r_B}{r}\right). \qquad (2\text{-}2\text{-}4)$$

The flow rate is

$$q = \frac{2\,\pi\, K\, W\, P_s}{\ln\left({r_B}/{r_s}\right)}. \qquad (2\text{-}2\text{-}5)$$

With reference to Figure 2-1, the pressure at the surface of the cake has the value,

$$P_s = \frac{1}{2}\,\rho\,\omega^2\,(r_s^2 - r_o^2) = \frac{1}{2}\,\rho\,(2\pi\, n\, r_B)^2\,(r_s^2 - r_o^2), \qquad (2\text{-}2\text{-}6)$$

where n is the rpm and ρ is the density of the liquid. From Equations (2-2-5) and (2-2-6), the following equation is derived,

$$q = \frac{dv}{dt} = \frac{\pi\, k\ \rho\, (2\pi\, n\, r_B)^2}{\mu \ln(r_B / r_s)} . \tag{2-2-7}$$

Equation (2-2-7) can be integrated to give

$$v = \frac{\pi\, k\, \rho\, (2\pi\, n\, r_B)^2}{\mu \ln(r_B / r_s)} \cdot t . \tag{2-2-8}$$

2-3 CAKE INCINERATION

Incineration may be considered as a method of solids destruction in the wastewater treatment field. The operating costs associated with this process are highly dependent on the net thermal value of the feed material. Mixing a dry and combustible material with the feed increases the net thermal value of the feed.

Sludge disposal is a major consideration in the planning and design of new wastewater treatment plants and in the expansion and upgrading of existing facilities. Along with the increasing difficulties of wastewater treatment facilities have shown that satisfactory treatment and disposal of sludge can be the most complex and costly operation in a municipal wastewater treatment system. A sludge disposal system that reduces the volume of material handled and disposed of, and saves or recovers energy is very desirable. If this system is cost-effective, the selection of a sludge disposal system is facilitated for particular communities.

Sewage sludge incineration has been practiced since the early part of the century. This method of sludge disposal was an adaptation of various industrial combustion processes developed during the latter part of the nineteenth century. Availability of cheap energy, limited capability of sludge dewatering equipment, and minimal or nonexistent air pollution requirements all led to the selection of incineration as a practical and inexpensive method of sludge disposal.

Increasing concern for air quality and experience with sludges from more advanced treatment processes, which are more difficult to dewater and require more energy to evaporate the excess water considerably reduced the enthusiasm for incineration. These problems, coupled with rising energy costs, increasing quantities of sludge, and limited resources, have led to the development of improved sludge dewatering methods and more efficient incineration equipment and systems.

Transportation of sewage sludge to its final disposal point demands maximum volume reduction and the highest solids content possible for efficient operation. Treatment methods used to achieve these goals include: sludge thickening followed by dewatering with vacuum filters, filter presses, or centrifuges. Incineration could be used with any of these process for ultimate volume reduction.

James and Kane (1991) studied sludge dewatering and incineration. They found that the use of dewatered sludge as a fuel in the bark boilers had little or no negative effect on their performance. And they also found the advent of new mechanical sludge dewatering equipment provided the paper industry with a new approach to sludge dewatering and represented a practical and profitable solution to one of the most challenging environmental issues facing the industry today; solid waste management.

Park and Kwon (1988) studied the dewaterability improvement and the heat recovery of cake incineration. They added pulverized fine coal into the sludge water to increase the heat values of sludge cakes for incineration. They found the required coal content ratio for natural incineration was practically one part coal to one part dried sludge.

Swanson and Bergstedt (1979) studied that coal could supply a heat source in sludge cake incineration. The coal had a heating value of 22 MJ/kg (9500 Btu/lb) and they could know the coal doses of roughly 50 to 75 g/kg wet cake were successful on replacing oil consumption during normal operation. They found an estimated 70 to 80 % reduction in oil use is possible by replacing with coal. Cost savings expected were somewhat offset by capital costs required for retrofitting to provide coal-handling facilities.

Hathaway and Olexsey (1977) studied sludge incineration and vacuum filtration with pulverized coal. They added pulverized coal into the sludge water to increase the vacuum filter yield, to increase the resultant sludge cake solids content, and to replace or reduce the amount of conditioning chemicals required for filtration of secondary sludge. And they also tried to replace or reduce the amount of high priced natural gas or fuel oil required for supplementary fuel in the sludge incineration operation.

Jackow (1976) pointed out that sludge incineration was based on different technologies than municipal refuse incineration. He mentioned also the conclusions of the 1972 EPA Sludge Incineration Task Force which is "When operated properly, today's sludge incinerator systems, which have been designed to meet existing air quality standards, have been shown by testing to produce acceptable stack emissions of particulate matter, nitrogen oxides, sulfur oxides and odor." He reported the locations of 22 sewage treatment plants with sludge energy saving systems. The list of the locations includes Central Contra Costa Sanitation District, Calif., Jacksonville, Fla, West Berlin,Ger., Granite, Ill., Louisville, Ky., Honolulu, Hawaii, Trinity River Authority, Tex., Kalamazoo, Mich., Wstern Branch Facility, Prince Georges County, Md., Green Bay, Wis., Grand Rapids, Mich., Clark County, Nev., Northwest Bergen County, N.J., Lansing, Mich, Somerset-Raritan, N.J., Atlantic County, N.J., Chesapeake-Elizabeth-Hampton Roads Sanitation District, Va., Oneida County, N.Y., Cleveland, Ohio, Hopewell, Va., Hazleton, Pa., and Hatfield, Pa..

Although the heat value of sludge is fairly high with 11.6 to 23.2 MJ/kg (5000 to 10000 Btu/lb) dry solids, the water content of most sludge cakes requires the addition of auxiliary fuel to maintain combustion in the furnace. Fuel cost is a major operational cost of incineration. The reduction of this cost can be achieved by raising the solids content of the sludge, thereby increasing the net heat value, or by lowering the amount of inert material in the sludge prior to incineration.

Sludge incineration can be considered to occur in four steps: 1) temperature of the sludge is raised to 100 ºC (212 ºF); 2) water is evaporated from the sludge; 3) water vapor temperature and air temperature are increased; and 4) temperature of the sludge is raised to the ignition point of the volatiles. The heat evolved by the incineration of sludge can be used in many ways, e.g., heating and drying of the incoming sludge cake, production of steam for space heating, powering mechanical equipment, or generating electricity. Because of relatively high temperature of the combustion gases, approximately 704 to 927 ºC (1300 to 1700 ºF), and the excess air injected into the furnace, a large amount of the heat evolved is used to raise the temperature of the incoming mixture of combustion air and fuel.

Table 2-1 shows the quantity of auxiliary fuel required for different cake moisture. The values were calculated on a theoretical basis for a sludge cake containing only water and sludge. In this table, the equivalency of 1000 Btu/lb equals 2.322 MJ/kg is used.

Table 2-1 Energy required for Sludge Cake (Basis : 1 ton of dry solids)
- Hathaway and Olexsey (1977)

Cake Moisture : Solids Ratio	Kg Water/ Ton Dry Solids	Energy Required to Drive off Water (MJ)	Energy Provided by Sludge Solids (MJ)	Auxiliary Energy Required (MJ)	Liters of Fuel Oil for Auxiliary Requirements
95:5	19000	1.12×10^5	1.7×10^4	9.50×10^4	2365
90:10	9000	5.33×10^4	1.7×10^4	3.63×10^4	904
85:15	5700	3.37×10^4	1.7×10^4	1.67×10^4	416
80:20	4000	2.34×10^4	1.7×10^4	6.4×10^3	159
75:25	3000	1.78×10^4	1.7×10^4	8.0×10^2	20
74.2:25.8	2870	1.7×10^4	1.7×10^4	0	0
70 :30	2300	1.36×10^4	1.7×10^4	-3.4×10^3	Autogenous
65:35	1900	1.12×10^4	1.7×10^4	-5.8×10	Autogenous

Table 2-1 shows an example calculation of auxiliary fuel requirements for sludge cake incineration. One ton of sludge solid is the basis of this calculation, and oil which has 40.17 MJ/*l* (17,300 Btu/*l*) is used for auxiliary fuel. The quantity of auxiliary fuel is calculated the requirement for different cake moisture values to maintain a multiple hearth incineration system at 427 °C (800 °F) off-gas temperature and 75 % excess air. 5.92 MJ/kg is used for energy required to drive off water, which is for latent heat of water vaporization (2.25 MJ/kg), off-gas temperature and excess air. These calculations are based on a sludge which has a heat value of 17 MJ/kg (7300 Btu/lb) of dry sludge solids. At a point corresponding to 25.8 % cake solids, the heat required to drive off the moisture equals the heat provided by the sludge solids.

CHAPTER 3

MATERIALS AND EXPERIMENTAL METHODS

3-1 SLUDGE SOURCES AND CONDITIONING MATERIALS

All experiments in this thesis used activated sludge from the 69th Street City of Houston Wastewater Treatment Plant. The sludge had a solids concentration of typically 2.0 % wt/wt. The typical characteristics of the sludge samples are shown in Table 3-1.

Table 3-1 Typical Sludge Characteristics in this Research

	Unit	Sludge
Solid Concentration	% (w/w)	2.0
Water Content	%	98.0
pH		7.0
Energy Content of Dry Solid	MJ/kg	13.9
Density	g/cm^3	1 (approximately)
Temperature	°C	20

All dewatering experiments were conducted by pouring a 200 ml raw sludge sample into a beaker. Polymer or kenaf conditioners were added to each sample prior to the mechanical dewatering by either filtration or centrifugation. After adding conditioners into sludge the samples were mixed for 2 min at 200 rpm for kenaf, and 5 min at 50 rpm for polymer. For kenaf the higher speed is required to mix the sample completely. For polymers, a lower mixing speed and longer mixing time are required to prevent dispersion of the flocs generated by the polymer addition.

The polymer was manufactured by STOCKHAUSEN, INC.. The reported contents of the polymer are acrylamide copolymer, hydrocarbon and surfactant. The polymer is a viscous, milky white emulsion with a mild odor of hydrocarbon and acrylate. The 69th Street Wastewater Treatment Plant provided the concentrated polymer and the characteristics of the polymer are shown in Table 3-2.

For comparative purposes unconditioned and conditioned sludge samples were grouped as follows:

(a) no conditioners

(b) with polymer

(c) with kenaf

(d) with polymer plus kenaf

Table 3-2 The Characteristics of Polyelectrolytes (Polymers)

Characteristics	
Boiling Point	98 ºC
Vapor Pressure	37 mmHg
Vapor Density (Air=1)	Greater than 1
Specific Gravity (H_2O=1)	1.02 @ 20 ºC
Melting Point	Less than 0 ºC
Evaporation Rate (Butyl Acetate =1)	Less than 1
Solubility in Water	Soluble = 0.5 % to 1 % maximum due to viscous nature of polymer solutions
Flash Point	Greater than 100 ºC

In category (a), the raw sludge was tested without any conditioner. Other conditions, such as filtration pressures, rotary speeds for centrifuge, and experiment time, were the same as other groupings of sludge experiments.

Polymer concentrations used in group (b) were 0.5 %, 1 %, 2 % and 3 %, and dosages were 10 ml, 20 ml and 30 ml. These polymer concentrations were made with water and the concentrated polymer provided by 69th Street Wastewater Treatment Plant.

Three different sizes (500 μm, 1000 μm, 1500 μm) of kenaf were used for the kenaf conditioning studies, and the dosages were 2.5 g, 5 g and 7.5 g. NATRA-SORB-C was used in this experiment, which was produced from a fiber plant called Kenaf. This particular kenaf has a reported absorbtion capacity of 4.5 *L* (1.2 gal) of oil per pound of dry kenaf.

A hammer mill was used to make kenaf powders in three different nominal sizes using stainless steel exit screens inside the grinder. A 500 μm screen was used to make kenaf with particle sizes less than 500 μm, etc. Figure 3-1 is a photograph of the hammer mill used to make different kenaf sizes.

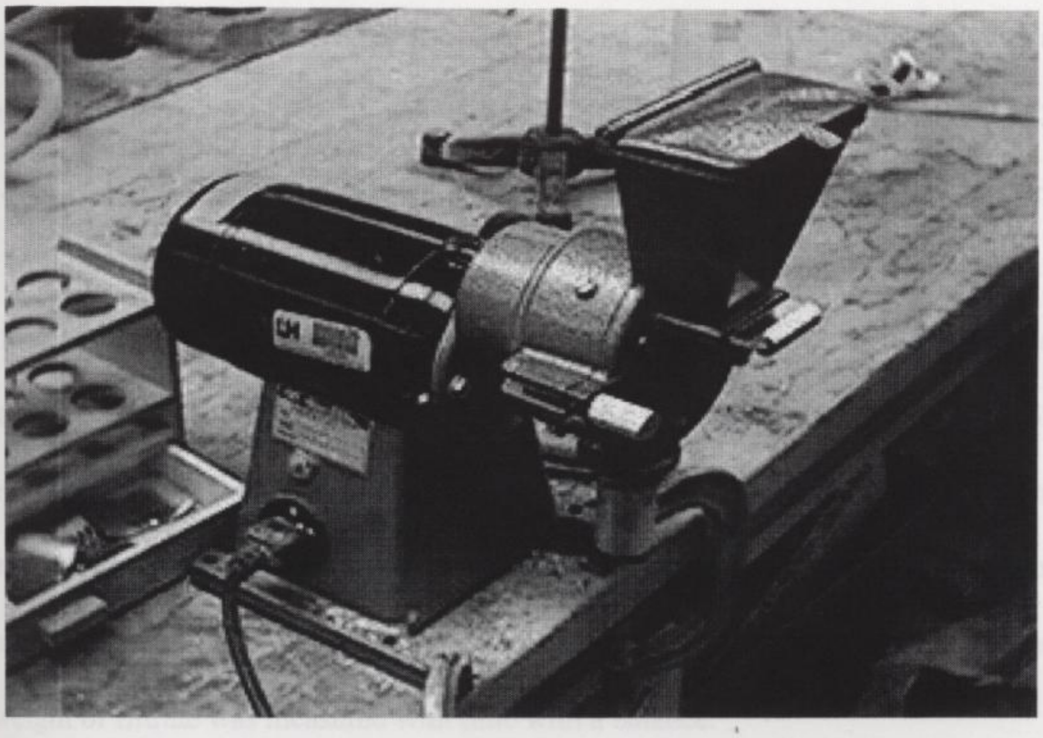

Figure 3-1 Picture of Bench Scale Hammer Mill

For group (d), 1 % polymer and 1000 μm of kenaf were blended for the experiments. The dosages of polymer were 10 ml, 20 ml and 30 ml, and for kenaf they were 2.5 g, 5 g and 7.5 g. At first kenaf was mixed at 200 rpm for 2 min, and then polymer was added into the sludge and kenaf mixture and mixed at 50 rpm for 5 min.

3-2 FILTRATION

Filtration was carried out in an acrylic cylinder 11 cm in diameter and 20 cm in height. Figure 3-2 shows the diagram of filtration setting. Nitrogen gas provided the pressure for filtration. The pressures for filtration were 68.9 kPa (10 psi), 103.4 kPa (15 psi) and 137.8 kPa (20 psi) for polymer filtration and 103.4 kPa (15 psi), 137.8 kPa (20 psi) and 172.3 kPa (25 psi) for kenaf filtration. For the samples of kenaf plus polymer the pressures were were 68.9 kPa (10 psi), 103.4 kPa (15 psi), 137.8 kPa (20 psi) and 172.3 kPa (25 psi). Rubber locking rings sealed the top and bottom of the filtration cylinder in order to prevent the pressure loss. Whatman No. 1 filter paper was put in the bottom of the filtration cylinder, and a wire mesh supported the filter paper. Figure 3-2 shows the diagram of filtration. A sludge sample conditioned by kenaf, polymer, or kenaf plus polymer was poured into the filtration cell and covered at the top. After fixing the pressure in the nitrogen tank regulator, the valves of the filtration cell were opened at the bottom and top of the cell. Filtrate was collected in the beaker under the filtration cell. The weight of filtrate was measured with time with a balance.

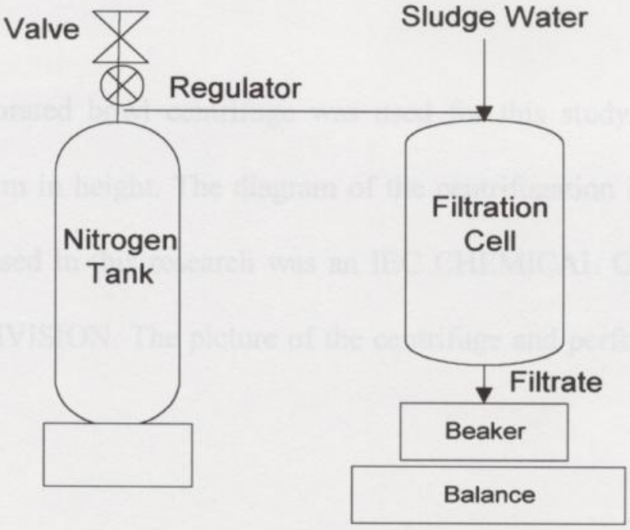

Figure 3-2 Diagram of Filtration

The filtration was stopped when the nitrogen gas bubbles would come out of the cylinder with filtrate. Figure 3-3 shows the picture of the filtration cell.

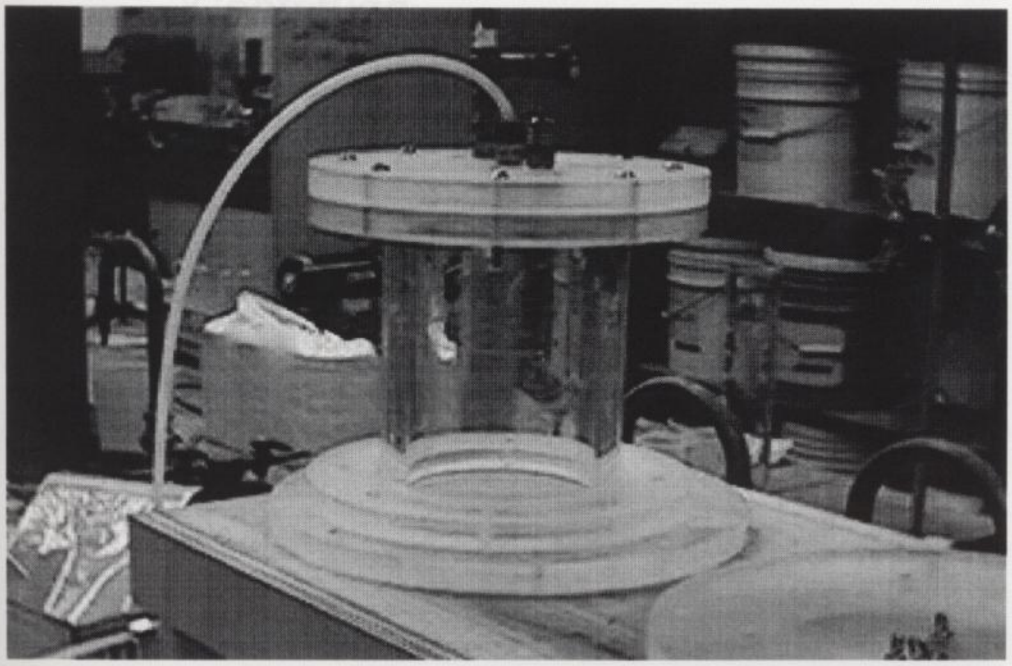

Figure 3-3 Picture of Filtration Cell

3-3 CENTRIFUGATION

The perforated bowl centrifuge was used for this study, which was 11 cm in diameter and 9 cm in height. The diagram of the centrifugation is shown in Figure 3-4. The centrifuge used in this research was an IEC CHEMICAL CENTRIFUGE made by DAMON/IEC DIVISION. The picture of the centrifuge and perforated bowl is shown in Figure 3-5.

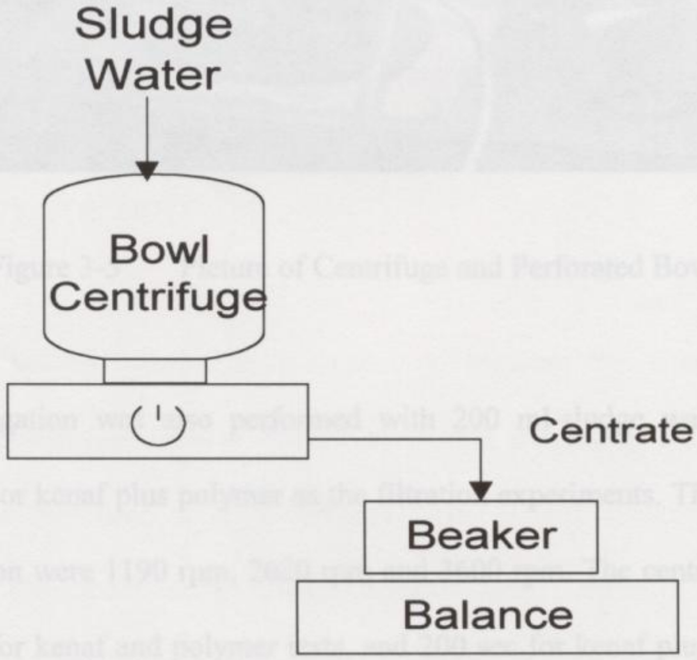

Figure 3-4 Diagram of Centrifugation

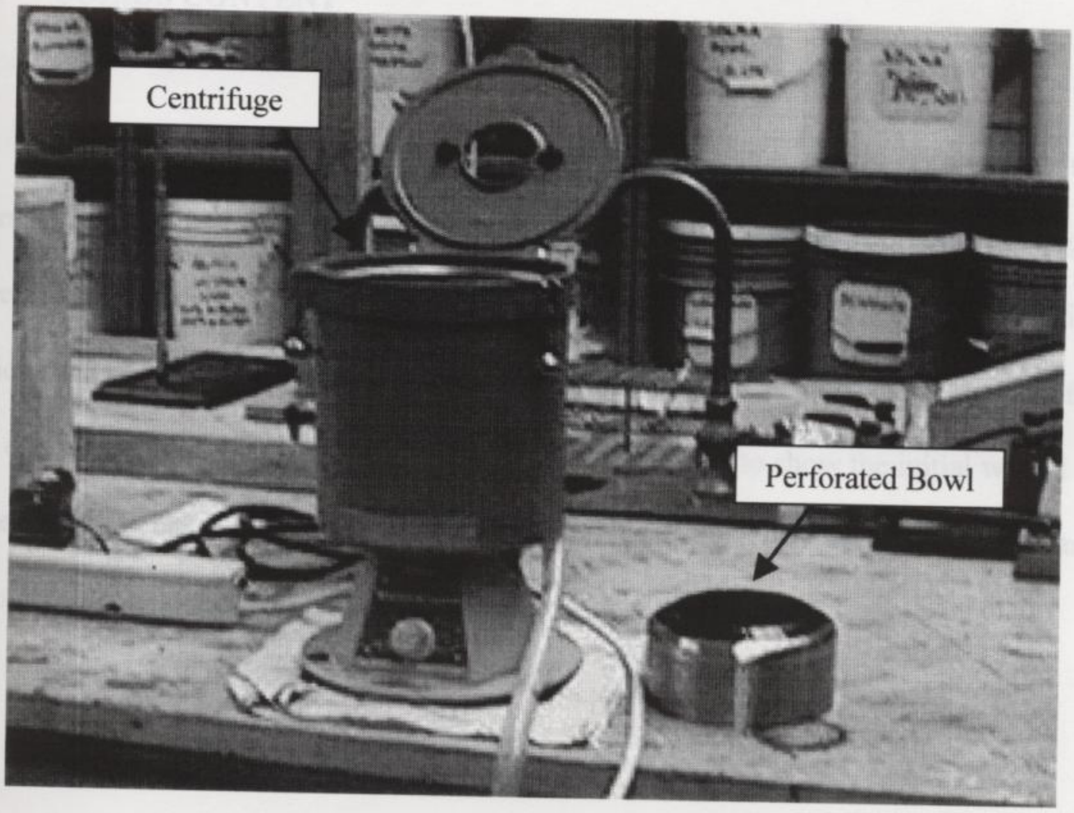

Figure 3-5 Picture of Centrifuge and Perforated Bowl

Centrifugation was also performed with 200 ml-sludge water conditioned by kenaf, polymer or kenaf plus polymer as the filtration experiments. The rotational speeds for centrifugation were 1190 rpm, 2620 rpm and 3600 rpm. The centrifugation time was about 600 sec for kenaf and polymer tests, and 200 sec for kenaf plus polymer test. The weight of centrate was measured with time in a beaker under the centrifuge setting using a balance. The moisture content and solid concentration were measured using the same method as filtration.

3-4 SOLIDS CONTENT

After filtration and centrifugation were finished, the solids content for the filtration and centrifugation cakes was measured. Solids content was expressed as weight percentages. A SARTORIUS MA 30-000V2 moisture balance was used to determine solids content. A filtration or centrifugation cake was put in the moisture balance and the top of the balance was closed. The balance was programmed to show the initial weight of cake, dry the cake at 130 ºC (266 ºF), and report the final weight of cake and automatically calculate solids content from the weight difference.

3-5 ENERGY CONTENT

A PARR-6000 calorimeter was used to measure the energy content of the filtration and centrifugation cakes. Before measuring the energy content of a cake, the calorimeter was standardized with Benzoic Acid. It was assumed that cakes were completely dry after the moisture balance measurement. Therefore, the energy content could be measured without any further drying procedure. The calorimeter reports energy content as Btu/lb and this value was converted to MJ/kg for reporting the results. The conversion factor used was that 1000 Btu/lb equaled 2.322 MJ/kg (Sawyer et al., 1994).

The subassemblies of the PARR calorimeter are a calorimeter, a water circulation pump, a water chiller, an oxygen bomb with a sample holder, and a printer. The system was all turned on and the temperature allowed to reach 35 °C (95 °F). A sample weighing between 0.5 g and 1 g, was put in the sample dish, and a 10 cm long ignition fuse was set slightly above the sample surface. One millimeter of distilled water was put in the bomb for quenching and the sample holder was inserted into the bomb and the top of the bomb closed. After assembly, the bomb was filled with oxygen gas. The bomb was put into the 2 *L* steel flask which was filled with 2 *L* distilled water. The two ignition lead wires were put into the terminal sockets on the bomb head and the calorimeter cover was closed. When the START button was pushed to initiate the test, SAMPLE ID and weight of sample were input. After 5 to 6 min, the calories measurement was finished and energy content of a sample was given. All the measurements were repeated three times per sample.

CHAPTER 4

EXPERIMENTAL RESULTS

4-1 SOLIDS CONTENT

The solids content of kenaf treated sludge processed by centrifugation is listed in Table 4-1. The solids content is reported as average solids content ± sample standard deviation based on three repeated experiments for each condition. The average solids content are between 14.0 % and 24.1 %, and the maximum sample standard deviation is 2.14. The 2.5 g, 5 g and 7.5 g kenaf dosages are used for each kenaf size and the raw sludge sample has 4g solids. The weight fractions of kenaf to dry solids in sludge sample are 0.625, 1.250 and 1.875 for 2.5 g, 5 g and 7.5 g kenaf dosages, respectively.

Figure 4-1 is a plot of the data shown in Table 4-1 for centrifugation with kenaf. The figure displays that the solids content of 3600 rpm are higher than those of 2620 rpm. The insignificant differences occurred when the 1.250 weight fraction of 500 μm kenaf is used. The solids content increased as the kenaf weight fractions increased, except for the 1.875 weight fractions of 1000 μm and 1500 μm kenaf. The kenaf sizes have no significant effects on the cake solids content. The 1.875 weight fraction of 500 μm kenaf at 3600 rpm produced the highest solids content in these experiments.

Table 4-1 Solids Content of Centrifugation with Kenaf

Kenaf Size (µm)	RPM Kenaf Weight Fraction	2620	3600
500	0.625	14.8 ± 0.67	16.9 ± 0.87
	1.250	17.9 ± 1.85	17.6 ± 1.51
	1.875	22.1 ± 0.47	24.1 ± 0.72
1000	0.625	15.0 ± 0.26	18.1 ± 0.10
	1.250	18.9 ± 1.15	20.8 ± 1.04
	1.875	17.8 ± 2.14	21.3 ± 1.91
1500	0.625	14.0 ± 0.78	18.0 ± 0.78
	1.250	18.0 ± 0.42	20.1 ± 0.35
	1.875	17.6 ± 0.78	21.7 ± 0.70

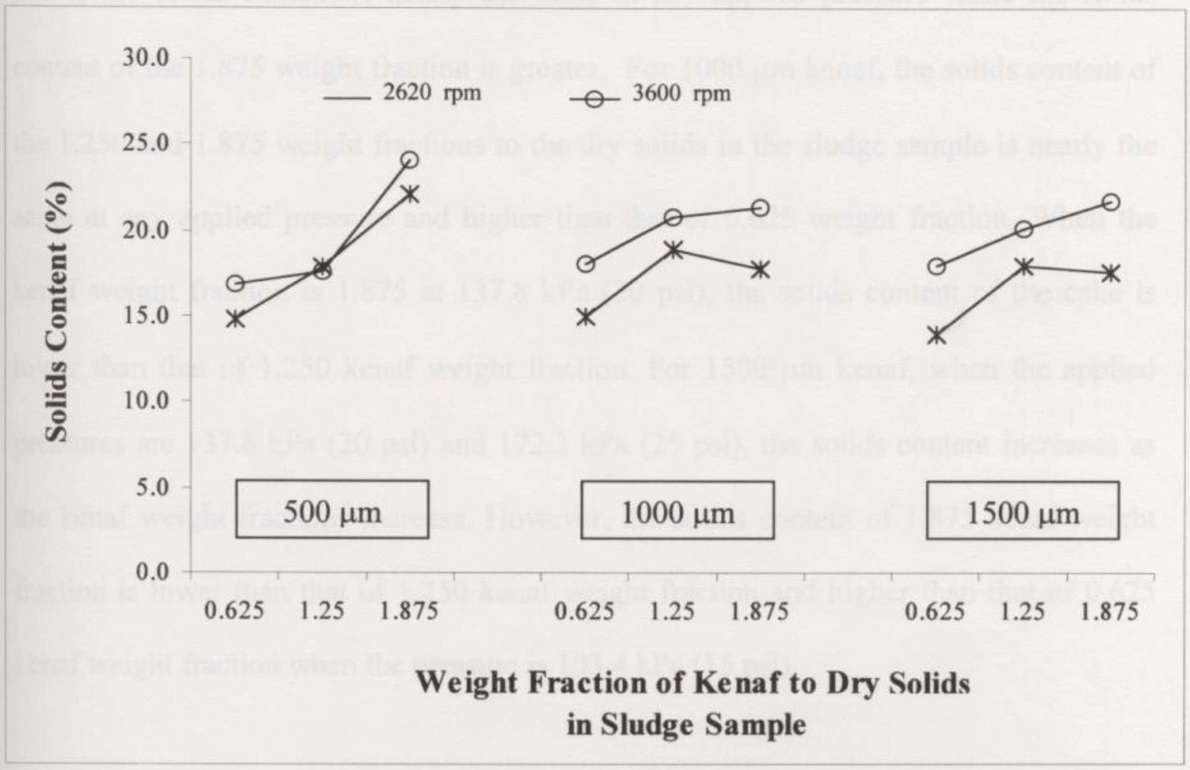

Figure 4-1 Solids Content of Centrifugation with Kenaf

The solids content of kenaf-treated sludge processed by filtration is listed in the Table 4-2. The average solids content is between 4.3 % and 20.0 %. The minimum standard deviation for three experiments per each condition is 0.15 and the maximum standard deviation for the three experiments was 2.10.

Figure 4-2 is a plot of the solids content from filtration with kenaf. The 1.875 weight fraction of 1500 μm kenaf at 172.3 kPa (25 psi) produced the highest solids content in these experiments. For most kenaf sizes and weight fractions, the solids content increased 67 % of the experiments as the applied pressures increased. The solids content of 0.625 weight fractions of all kenaf sizes at all the applied filtration pressures is essentially the same. For 500 μm kenaf, when the kenaf weight fractions are 0.625 and 1.250, the solids content is nearly the same at any applied pressure while the solids content of the 1.875 weight fraction is greater. For 1000 μm kenaf, the solids content of the 1.250 and 1.875 weight fractions to the dry solids in the sludge sample is nearly the same at any applied pressure and higher than that of 0.625 weight fraction. When the kenaf weight fraction is 1.875 at 137.8 kPa (20 psi), the solids content of the cake is lower than that of 1.250 kenaf weight fraction. For 1500 μm kenaf, when the applied pressures are 137.8 kPa (20 psi) and 172.3 kPa (25 psi), the solids content increases as the kenaf weight fractions increase. However, the solids content of 1.875 kenaf weight fraction is lower than that of 1.250 kenaf weight fraction and higher than that of 0.625 kenaf weight fraction when the pressure is 103.4 kPa (15 psi).

Table 4-2 Solids content of Filtration with Kenaf

Kenaf Size (µm)	Pressure (kPa) / Kenaf Weight Fraction	103.4	137.8	172.3
500	0.625	4.3 ± 0.21	6.0 ± 0.32	8.4 ± 0.80
	1.250	5.0 ± 0.67	4.7 ± 0.40	8.1 ± 0.21
	1.875	6.4 ± 1.36	13.5 ± 1.00	13.5 ± 2.10
1000	0.625	5.6 ± 0.44	7.1 ± 0.17	6.0 ± 0.36
	1.250	14.1 ± 1.29	18.0 ± 0.40	18.6 ± 0.72
	1.875	15.3 ± 0.40	16.1 ± 0.15	18.6 ± 0.32
1500	0.625	5.2 ± 0.72	5.3 ± 0.80	5.4 ± 1.10
	1.250	13.3 ± 0.21	15.3 ± 0.25	15.6 ± 1.04
	1.875	12.3 ± 0.47	17.0 ± 0.26	20.0 ± 0.55

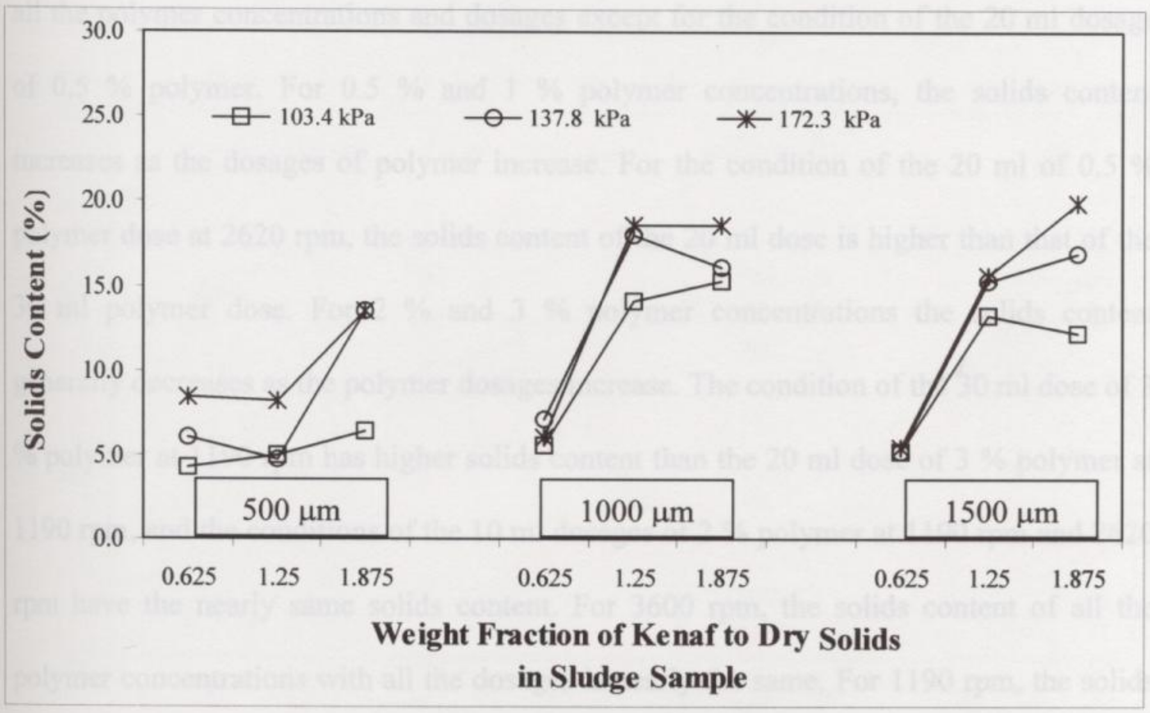

Figure 4-2 Solids content of Filtration with Kenaf

The solids content of polymer treated sludge processed by centrifugation is listed in Table 4-3. The rotational speeds used for the polymer centrifugation are 1190 rpm, 2620 rpm and 3600 rpm. The average solids content of the centrifugation with polymer is between 7.9 % and 23.7 %. And the minimum sample standard deviation of three experiments per each condition is 0.0, and the maximum standard deviation is 2.29. For the 30 ml dosage of 3 % polymer at 2620 rpm, only one experiment could be conducted, and for the 30ml dosage of 3 % polymer at 3600 rpm, there is no data because a lot of sludge particles passed through the centrifuge bowl.

Figure 4-3 is a plot of the solids content for polymer-treated sludge processed by centrifugation. A rotation speed of 3600 rpm produces the driest centrifugation cakes for all the polymer concentrations and dosages except for the condition of the 20 ml dosage of 0.5 % polymer. For 0.5 % and 1 % polymer concentrations, the solids content increases as the dosages of polymer increase. For the condition of the 20 ml of 0.5 % polymer dose at 2620 rpm, the solids content of the 20 ml dose is higher than that of the 30 ml polymer dose. For 2 % and 3 % polymer concentrations the solids content generally decreases as the polymer dosages increase. The condition of the 30 ml dose of 3 % polymer at 1190 rpm has higher solids content than the 20 ml dose of 3 % polymer at 1190 rpm, and the conditions of the 10 ml dosages of 2 % polymer at 1190 rpm and 2620 rpm have the nearly same solids content. For 3600 rpm, the solids content of all the polymer concentrations with all the dosages is nearly the same. For 1190 rpm, the solids content of 0.5 % and 1 % polymer concentrations is lower than that of 2 % and 3 % polymer concentrations.

Table 4-3 Solids content of Centrifugation with Polymer

Conc. (%)	Polymer Dosage(ml) \ RPM	1190	2620	3600
0.5	10	7.9 ± 1.06	12.9 ± 0.35	17.1 ± 0.35
	20	10.7 ± 0.40	20.3 ± 0.56	19.2 ± 0.29
	30	14.6 ± 0.12	18.9 ± 0.25	22.5 ± 0.53
1	10	10.8 ± 0.72	16.1 ± 0.44	18.1 ± 0.20
	20	11.7 ± 0.40	16.5 ± 0.20	20.4 ± 0.74
	30	12.2 ± 0.32	19.3 ± 0.72	22.0 ± 0.42
2	10	19.3 ± 2.29	19.9 ± 0.31	22.6 ± 0.32
	20	17.0 ± 0.58	19.1 ± 0.59	21.0 ± 0.55
	30	16.2 ± 0.21	18.4 ± 0.12	20.9 ± 0.52
3	10	15.9 ± 0.00	22.9 ± 0.70	23.7 ± 0.15
	20	14.6 ± 0.78	21.2 ± 1.59	22.7 ± 0.40
	30	18.7 ± 1.03	20.6	

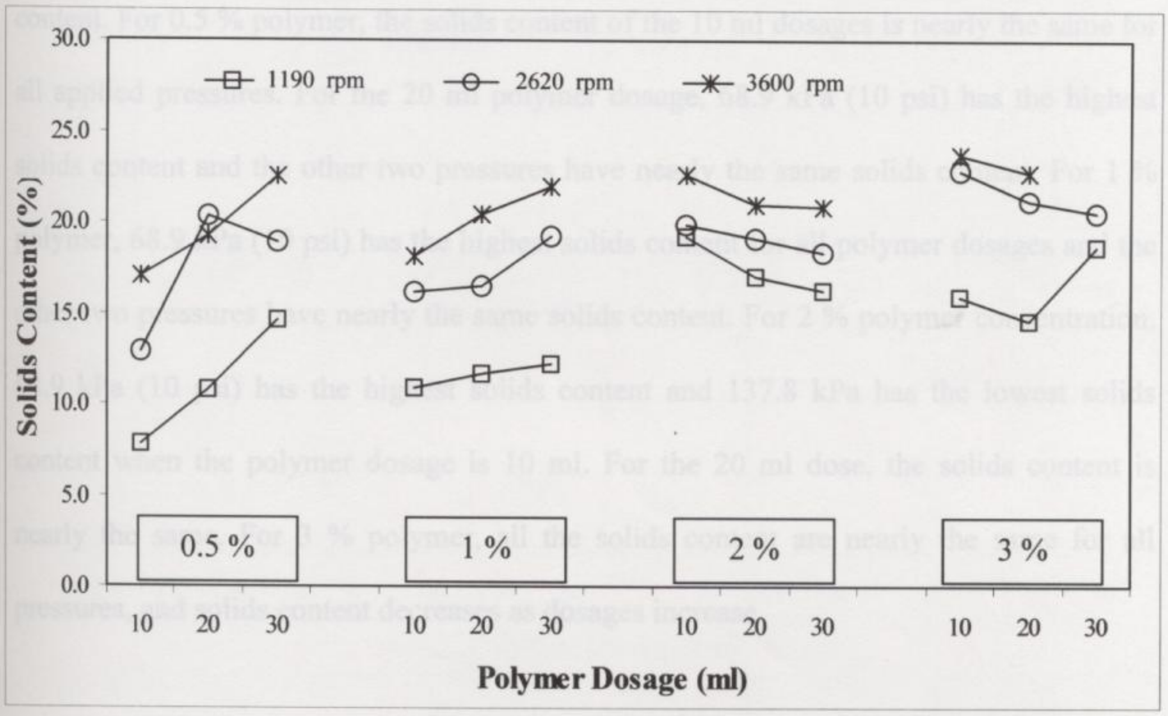

Figure 4-3 Solids content of Centrifugation with Polymer

The solids content of polymer-treated sludge processed by filtration is listed in Table 4-4. Three different filtration pressures applied for this filtration are 68.9 kPa (10 psi), 103.4 kPa (15 psi) and 137.8 kPa (20 psi). The average solids content of the filtration with polymer is between 12.2 % and 17.9 %. The minimum sample standard deviation of tree experiments for each condition is 0.06 and the maximum standard deviation is 0.89. For several conditions, there are no data because the slurry passed through the filtration cell without any solids retention.

Figure 4-4 is a plot of solids content for polymer-treated sludge processed by filtration. There is no significant difference between solids content for all conditions. The conditions of the 10 ml dose of 3 % polymer have the highest solids content and the conditions of the 103.4 kPa (15 psi) and 137.8 kPa (20 psi) have the lowest solids content. For 0.5 % polymer, the solids content of the 10 ml dosages is nearly the same for all applied pressures. For the 20 ml polymer dosage, 68.9 kPa (10 psi) has the highest solids content and the other two pressures have nearly the same solids content. For 1 % polymer, 68.9 kPa (10 psi) has the highest solids content for all polymer dosages and the other two pressures have nearly the same solids content. For 2 % polymer concentration, 68.9 kPa (10 psi) has the highest solids content and 137.8 kPa has the lowest solids content when the polymer dosage is 10 ml. For the 20 ml dose, the solids content is nearly the same. For 3 % polymer, all the solids content are nearly the same for all pressures, and solids content decreases as dosages increase.

Table 4-4 Solids content of Filtration with Polymer

Conc. (%)	Pressure (kPa) / Polymer Dosage (ml)	68.9	103.4	137.8
0.5	10	14.6 ± 0.70	14.1 ± 0.25	14.6 ± 0.53
	20	16.5 ± 0.17	15.1 ± 0.40	15.4 ± 0.38
	30	15.0 ± 0.21	14.7 ± 0.12	15.9 ± 0.23
1	10	15.9 ± 0.36	13.4 ± 0.62	13.1 ± 0.83
	20	14.8 ± 0.35	12.7 ± 0.47	12.2 ± 0.26
	30	15.1 ± 0.06	13.2 ± 0.47	13.7 ± 0.46
2	10	15.9 ± 0.36	15.3 ± 0.40	14.2 ± 0.15
	20	14.5 ± 0.29	15.2 ± 0.06	14.9 ± 0.40
	30			
3	10	16.8 ± 0.36	17.3 ± 0.66	17.9 ± 0.40
	20	14.8 ± 0.40	15.4 ± 0.89	14.6 ± 0.56
	30	14.4 ± 0.66		

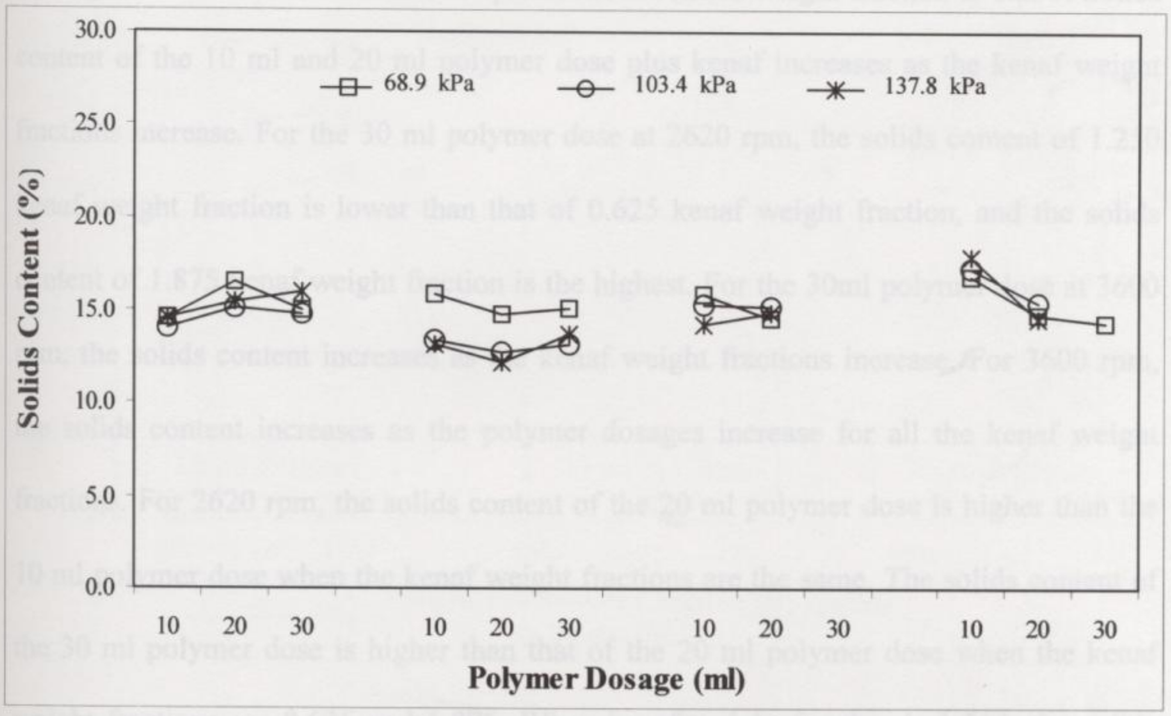

Figure 4-4 Solids content of Filtration with Polymer

The solids content of a kenaf-polymer blend treated sludge processed by centrifugation is listed in Table 4-5. The blend used was 1 % polymer with 1000 μm kenaf at 2620 rpm and 3600 rpm. The polymer dosages are 10 ml, 20 ml and 30 ml and the kenaf weight fractions to the dry solids in the sludge samples are 0.625, 1.250 and 1.875. The average solids content of triple experiments per each condition are between 16.2 % and 30.2 %. The maximum standard deviation is 0.85.

Figure 4-5 is a graph of solids content for kenaf-polymer treated sludge processed by centrifugation. For the 10 ml and 20 ml dosages, 3600 rpm has higher solids content than 2620 rpm. For the dosage of 30 ml polymer, the solids content of 0.625 and 1.875 kenaf weight fraction to the dry solids in sludge sample is nearly the same, and 3600 rpm has higher solids content than 2620 rpm when the kenaf weight fraction is 1.250. Solids content of the 10 ml and 20 ml polymer dose plus kenaf increases as the kenaf weight fractions increase. For the 30 ml polymer dose at 2620 rpm, the solids content of 1.250 kenaf weight fraction is lower than that of 0.625 kenaf weight fraction, and the solids content of 1.875 kenaf weight fraction is the highest. For the 30ml polymer dose at 3600 rpm, the solids content increases as the kenaf weight fractions increase. For 3600 rpm, the solids content increases as the polymer dosages increase for all the kenaf weight fractions. For 2620 rpm, the solids content of the 20 ml polymer dose is higher than the 10 ml polymer dose when the kenaf weight fractions are the same. The solids content of the 30 ml polymer dose is higher than that of the 20 ml polymer dose when the kenaf weight fractions are 0.625 and 1.875. When kenaf weight fraction is 1.250, the solids content of the 20 ml and 30 ml polymer dosages is nearly the same.

Table 4-5 Solids content of Centrifugation with 1 % Polymer and 1000 μm Kenaf

Polymer Dosage (ml)	RPM / Kenaf Weight Fraction	2620	3600
10	0.625	16.2 ± 0.42	18.4 ± 0.57
	1.250	19.7 ± 0.62	24.3 ± 0.59
	1.875	21.0 ± 0.31	24.4 ± 0.26
20	0.625	19.0 ± 0.53	22.1 ± 0.35
	1.250	23.0 ± 0.12	27.0 ± 0.06
	1.875	25.2 ± 0.15	29.2 ± 0.26
30	0.625	22.5 ± 0.21	23.2 ± 0.40
	1.250	21.9 ± 0.15	28.9 ± 0.30
	1.875	30.0 ± 0.46	30.2 ± 0.85

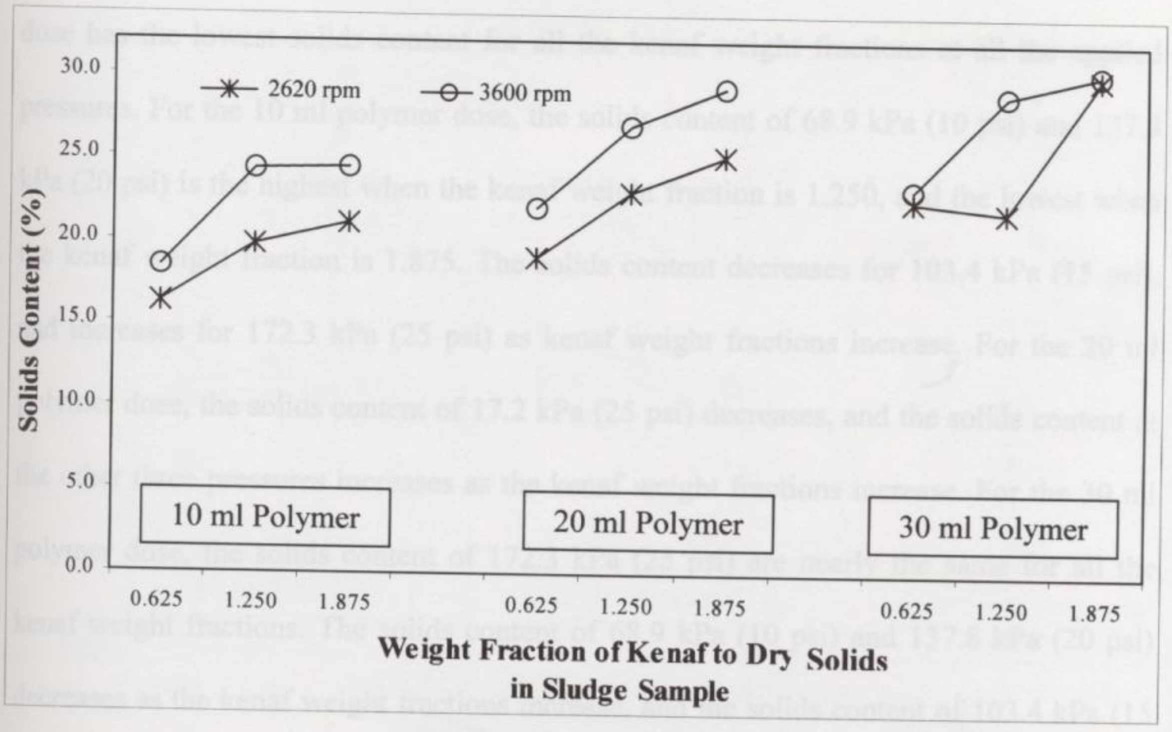

Figure 4-5 Solids Content of Centrifugation with Polymer and Kenaf

The solids content of a kenaf-polymer blend treated sludge processed by filtration is listed in Table 4-6. The blend used was three different dosages of 1 % polymer with three different 1000 μm kenaf weight fractions to dry solids in sludge sample. The applied pressures for this filtration are 68.9 kPa (10 psi), 103.4 kPa (15 psi), 137.8 kPa (20 psi), and 172.3 kPa (25 psi). The average solids content is between 13.1 % and 19.4 %. The maximum standard deviation for triple solids content per each condition is 0.67.

Figure 4-6 shows a graph of solids content for kenaf-polymer treated sludge processed by filtration. In many conditions, 172.3 kPa (25 psi) has the highest solids content and 68.9 kPa (10 psi) has the lowest solids content. The solids content of the 30 ml polymer dose are the highest for all the kenaf weight fractions. The 10 ml polymer dose has the lowest solids content for all the kenaf weight fractions at all the applied pressures. For the 10 ml polymer dose, the solids content of 68.9 kPa (10 psi) and 137.8 kPa (20 psi) is the highest when the kenaf weight fraction is 1.250, and the lowest when the kenaf weight fraction is 1.875. The solids content decreases for 103.4 kPa (15 psi), and increases for 172.3 kPa (25 psi) as kenaf weight fractions increase. For the 20 ml polymer dose, the solids content of 17.2 kPa (25 psi) decreases, and the solids content at the other three pressures increases as the kenaf weight fractions increase. For the 30 ml polymer dose, the solids content of 172.3 kPa (25 psi) are nearly the same for all the kenaf weight fractions. The solids content of 68.9 kPa (10 psi) and 137.8 kPa (20 psi) decreases as the kenaf weight fractions increase, and the solids content of 103.4 kPa (15 psi) and 172.3 kPa (25 psi) is the highest when the kenaf weight fraction is 1.250.

Table 4-6 Solids Content of Filtration with 1% Polymer and 1000 µm Kenaf

Polymer Dosage (ml)	Pressure (kPa) / Kenaf Weight Fraction	68.9	103.4	137.8	172.3
10	0.625	14.3 ± 0.45	16.6 ± 0.44	15.1 ± 0.31	14.9 ± 0.29
	1.250	14.9 ± 0.25	15.4 ± 0.26	16.1 ± 0.21	16.5 ± 0.25
	1.875	13.5 ± 0.59	14.8 ± 0.36	13.1 ± 0.64	17.4 ± 0.47
20	0.625	15.1 ± 0.15	15.8 ± 0.26	14.5 ± 0.67	17.7 ± 0.32
	1.250	15.6 ± 0.45	16.4 ± 0.56	18.2 ± 0.12	16.8 ± 0.36
	1.875	13.7 ± 0.35	15.3 ± 0.40	15.2 ± 0.26	15.8 ± 0.40
30	0.625	16.8 ± 0.35	15.9 ± 0.45	18.5 ± 0.38	18.8 ± 0.17
	1.250	17.8 ± 0.21	18.4 ± 0.31	17.8 ± 0.36	19.4 ± 0.15
	1.875	17.1 ± 0.25	15.0 ± 0.67	17.4 ± 0.29	19.0 ± 0.21

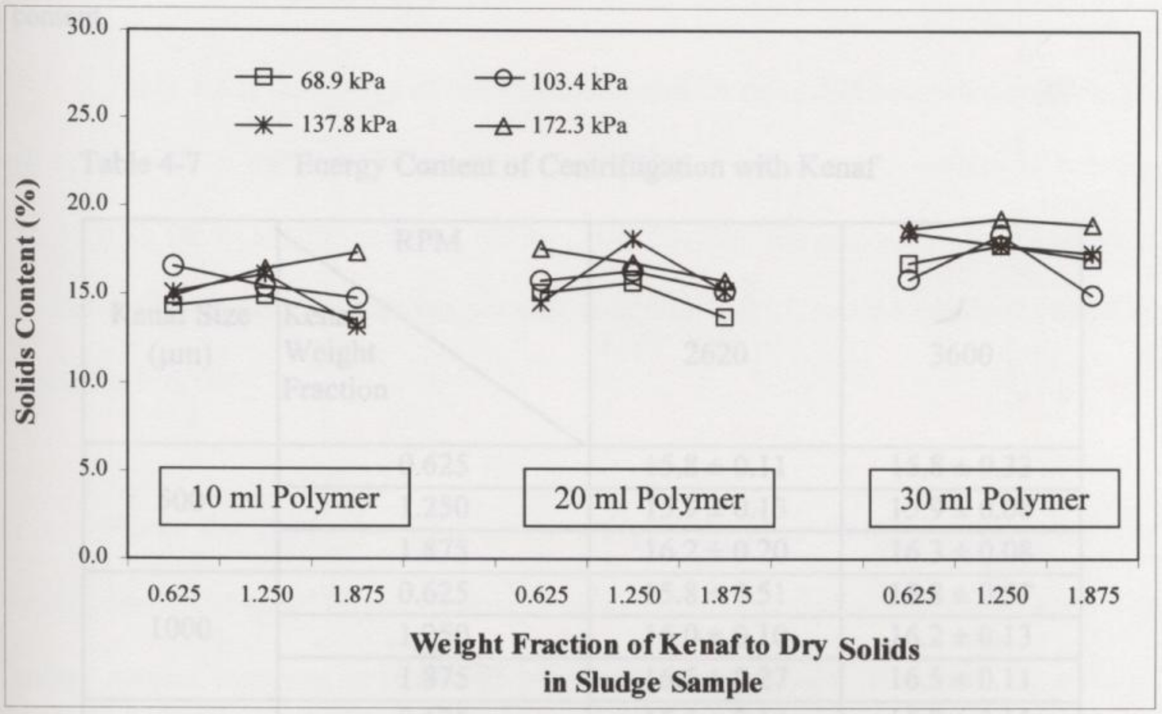

Figure 4-6 Solids Content of Filtration with Polymer and Kenaf

4-2 ENERGY CONTENT

Table 4-7 displays the data of the energy content of centrifugation with three different dosages and sizes of kenaf at 2620 rpm and 3600 rpm. The average energy content is 15.5 MJ/kg (6675 Btu/lb) and 16.5 MJ/kg (7106 Btu/lb). The minimum sample standard deviation is 0.08 and the maximum standard deviation for three energy content per each condition is 0.57.

Figure 4-7 shows the result of energy content of centrifugation with kenaf. All the energy content with kenaf is much higher than the energy content of raw sludge cake. The energy content of centrifugation cakes increases as the kenaf weight fractions increase. However, the kenaf sizes and the rotational speeds have no effect on the energy content.

Table 4-7 Energy Content of Centrifugation with Kenaf

Kenaf Size (μm)	RPM Kenaf Weight Fraction	2620	3600
500	0.625	15.8 ± 0.11	15.8 ± 0.33
	1.250	15.9 ± 0.13	15.9 ± 0.08
	1.875	16.2 ± 0.20	16.3 ± 0.08
1000	0.625	15.8 ± 0.51	15.8 ± 0.57
	1.250	16.0 ± 0.10	16.2 ± 0.13
	1.875	16.5 ± 0.27	16.5 ± 0.11
1500	0.625	15.5 ± 0.14	15.8 ± 0.11
	1.250	15.9 ± 0.16	15.9 ± 0.10
	1.875	16.3 ± 0.21	16.5 ± 0.22

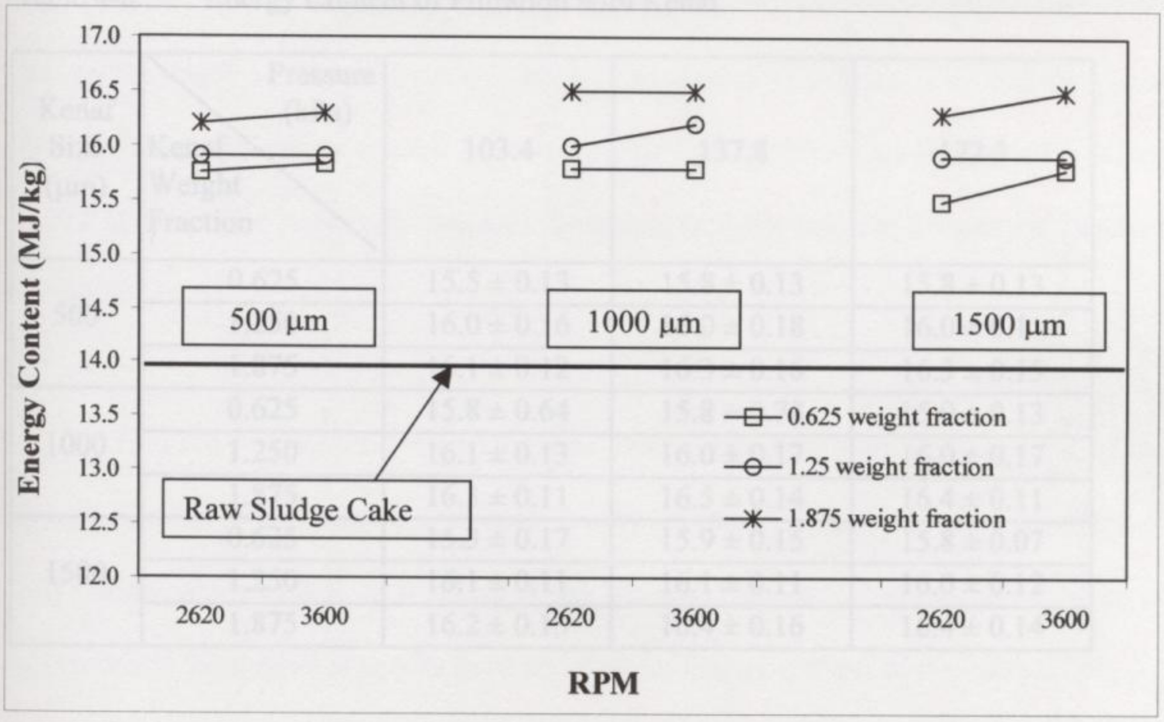

Figure 4-7 Energy Content of Centrifugation with Kenaf

Table 4-8 is the energy content of filtration with three different sizes and dosages of kenaf at three different filtration pressures. The average energy content is between 15.3 MJ/kg (6589 Btu/lb) and 16.5 MJ/kg (7106 Btu/lb). The minimum sample standard deviation for the three experiments per each condition is 0.07, and the maximum standard deviation is 0.78.

Figure 4-8 shows the result of the energy content of filtration with kenaf. The energy content of kenaf filtration cakes is much higher than that of raw sludge cake. The energy content increases as the kenaf weight fractions increase. However, the sizes of kenaf and the applied filtration pressures have no effect on the energy content.

Table 4-8 Energy Content of Filtration with Kenaf

Kenaf Size (μm)	Kenaf Weight Fraction \ Pressure (kPa)	103.4	137.8	172.3
500	0.625	15.5 ± 0.13	15.8 ± 0.13	15.8 ± 0.13
	1.250	16.0 ± 0.16	16.0 ± 0.18	16.0 ± 0.11
	1.875	16.1 ± 0.12	16.3 ± 0.16	16.3 ± 0.15
1000	0.625	15.8 ± 0.64	15.8 ± 0.78	15.9 ± 0.13
	1.250	16.1 ± 0.13	16.0 ± 0.17	16.0 ± 0.17
	1.875	16.3 ± 0.11	16.5 ± 0.14	16.4 ± 0.11
1500	0.625	15.3 ± 0.17	15.9 ± 0.15	15.8 ± 0.07
	1.250	16.1 ± 0.11	16.1 ± 0.11	16.0 ± 0.12
	1.875	16.2 ± 0.13	16.4 ± 0.16	16.4 ± 0.14

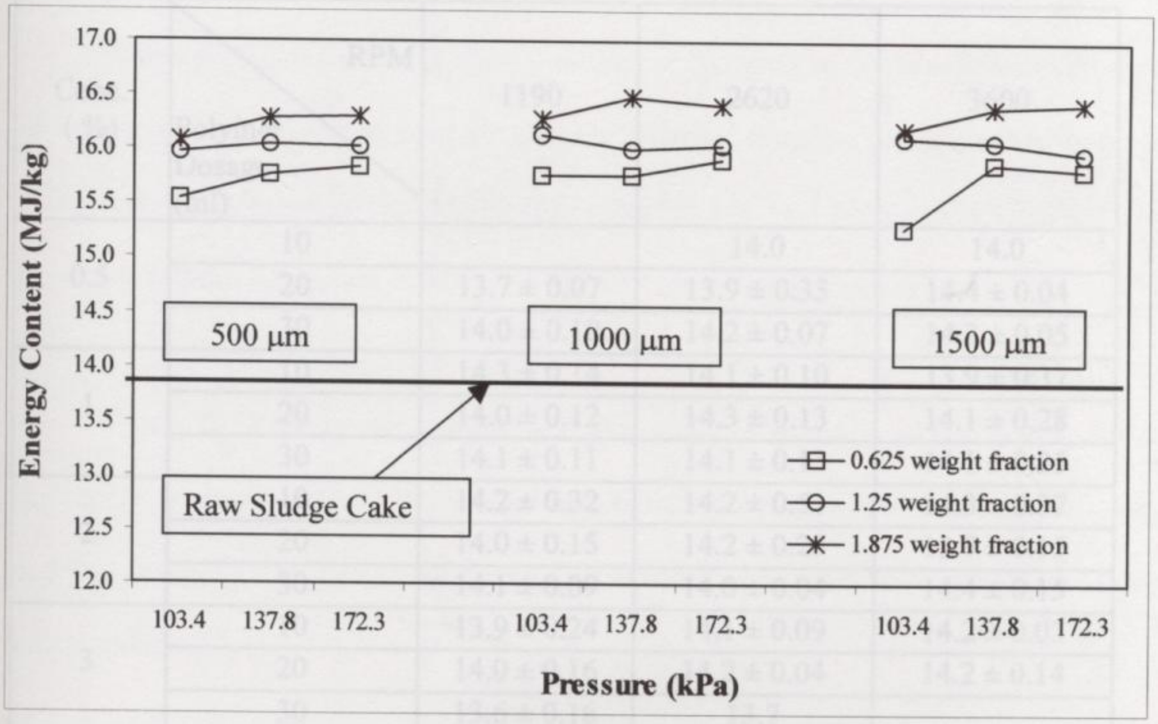

Figure 4-8 Energy Content of Filtration with Kenaf

Table 4-9 shows the result of the energy content of centrifugation with three different dosages of various concentrations of polymer at 1190 rpm, 2620 rpm and 3600 rpm. The average energy content is between 13.6 MJ/kg (5857 Btu/lb) and 14.4 MJ/kg (6202 Btu/lb). The minimum standard deviation is 0.03, and the maximum standard deviation is 0.51.

Figure 4-9 shows the energy content of centrifugation with polymer. All of the energy content of the centrifugation cakes with polymer is about the energy content of raw sludge cake which is 13.9 MJ/kg (5986 Btu/lb). The concentrations and dosages of polymer and the rotational speeds have no effect on energy content of the cakes.

Table 4-9 Energy Content of Centrifugation with Polymer

Conc. (%)	RPM / Polymer Dosage (ml)	1190	2620	3600
0.5	10		14.0	14.0
	20	13.7 ± 0.07	13.9 ± 0.33	14.4 ± 0.04
	30	14.0 ± 0.10	14.2 ± 0.07	14.3 ± 0.05
1	10	14.3 ± 0.14	14.1 ± 0.10	13.9 ± 0.37
	20	14.0 ± 0.12	14.3 ± 0.13	14.1 ± 0.28
	30	14.1 ± 0.11	14.1 ± 0.13	14.1 ± 0.25
2	10	14.2 ± 0.32	14.2 ± 0.51	14.3 ± 0.37
	20	14.0 ± 0.15	14.2 ± 0.23	13.9 ± 0.15
	30	14.1 ± 0.09	14.0 ± 0.04	14.4 ± 0.15
3	10	13.9 ± 0.24	14.1 ± 0.09	14.2 ± 0.03
	20	14.0 ± 0.16	14.2 ± 0.04	14.2 ± 0.14
	30	13.6 ± 0.16	13.7	

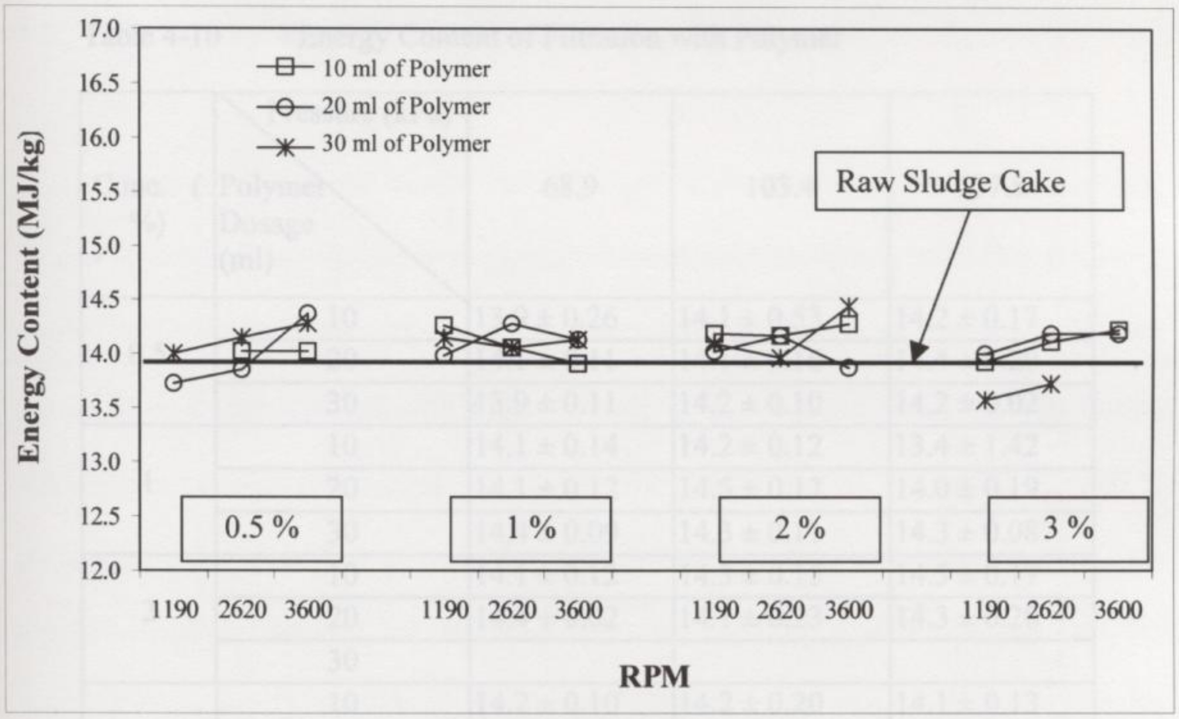

Figure 4-9 Energy Content of Centrifugation with Polymer

Table 4-10 is the result of energy content of filtration with three different dosages of various concentrations of polymer at three different filtration pressures. The average energy content is between 13.4 MJ/kg (5771 Btu/lb) and 14.5 MJ/kg (6245 Btu/lb). The minimum standard deviation is 0.02, and the maximum standard deviation is 1.42.

Figure 4-10 shows the result of energy content of filtration with polymer. All of the energy content is around the energy content of raw sludge cake. The concentrations and the dosages of polymer and the applied filtration pressures have no effect on the energy content.

Table 4-10 Energy Content of Filtration with Polymer

Conc. (%)	Polymer Dosage (ml) \ Pressure (kPa)	68.9	103.4	137.8
0.5	10	13.9 ± 0.26	14.1 ± 0.53	14.2 ± 0.17
	20	14.1 ± 0.11	14.1 ± 0.16	14.4 ± 0.20
	30	13.9 ± 0.11	14.2 ± 0.10	14.2 ± 0.02
1	10	14.1 ± 0.14	14.2 ± 0.12	13.4 ± 1.42
	20	14.1 ± 0.12	14.5 ± 0.17	14.0 ± 0.19
	30	14.4 ± 0.09	14.3 ± 0.11	14.3 ± 0.08
2	10	14.1 ± 0.12	14.3 ± 0.15	14.5 ± 0.17
	20	14.4 ± 0.02	14.1 ± 0.23	14.3 ± 0.20
	30			
3	10	14.2 ± 0.10	14.2 ± 0.20	14.1 ± 0.13
	20	13.9 ± 0.15	14.0 ± 0.24	14.0 ± 0.32
	30	14.0 ± 0.13		

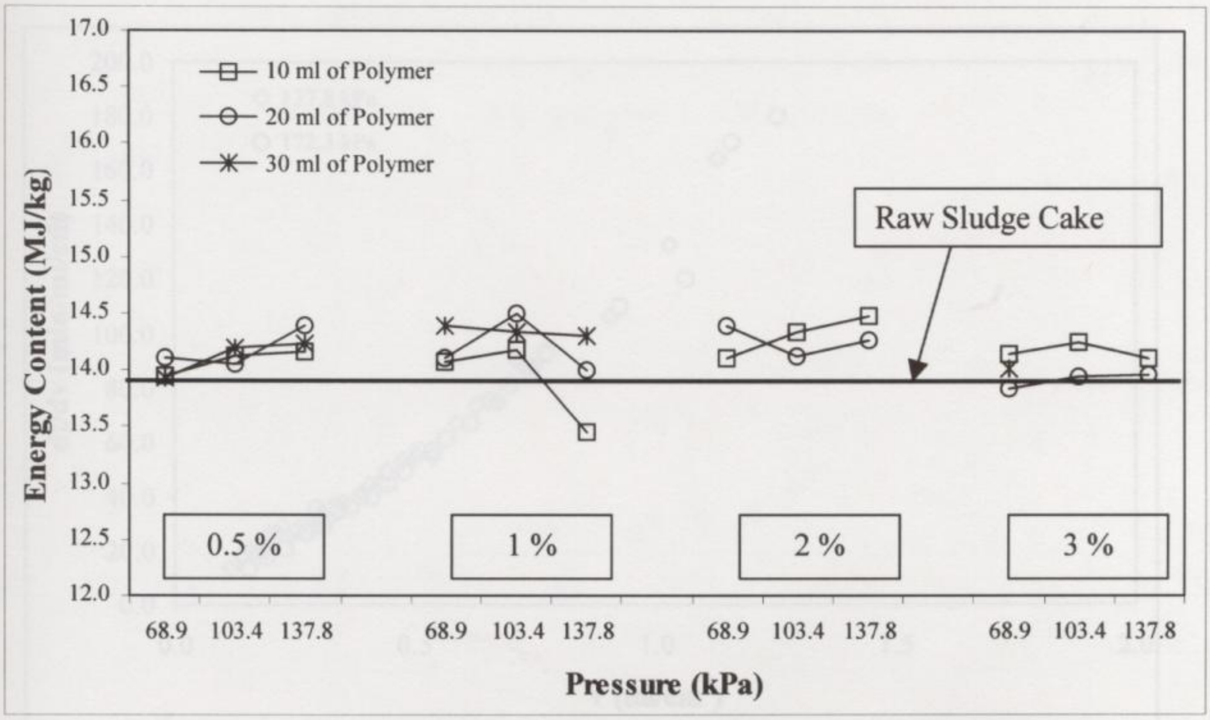

Figure 4-10 Energy Content of Filtration with Polymer

4-3 FILTRATE RATES

Figure 4-11 is a plot of *dt/dv* (min/ml/cm^2) versus *v* (ml/cm^2) with a raw sludge sample for each of several different pressure conditions. The filtrate rate (*q*) is 1/(*dt/dv*). According to Equation (2-1-8), the slope of this graph represents the specific resistance (α) and the Y-intercept indicates the resistance of the medium (*R*). Until the filtrate volume/area of filter (*v*) reaches 0.5 ml/cm^2, the filtrate rate of 172.3 kPa (25 psi) is somewhat higher than that of the 137.8 kPa (20 psi) pressure condition. Beyond that point, the filtrate rates of the 137.8 kPa (20 psi) and 172.3 kPa (25 psi) pressure conditions are nearly the same. The specific resistance of this experiment remains constant, and after *v* is 0.5 ml/cm^2; the specific resistance increases with *v*.

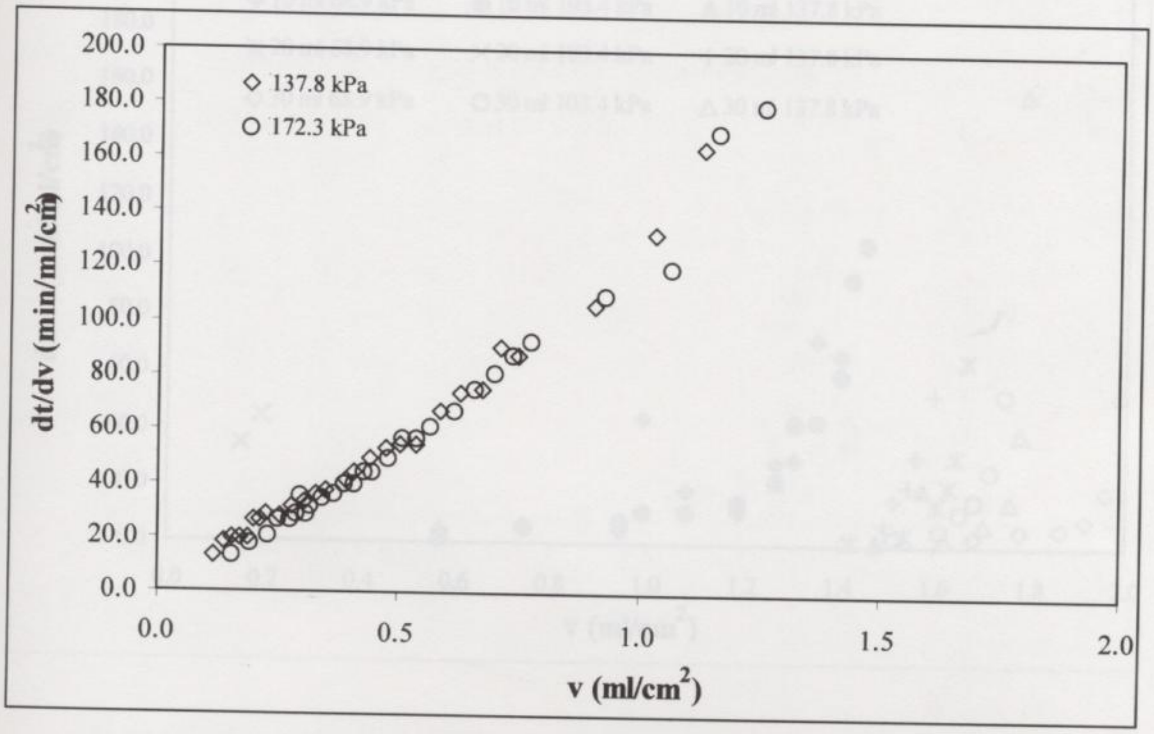

Figure 4-11 *dt/dv* Versus Filtrate Volume with Raw Sludge

Figure 4-12 shows the result of *dt/dv* versus *v* with various dosages of the concentration of 0.5 % polymer for three different applied pressures. The filtrate rates decrease with *v* for all conditions. The specific resistances of these polymer experiments increase with *v*; the specific resistances increase dramatically after certain *v* values. All the filtrate rates are higher than that of the raw sludge sample. The filtrate rates of the 10 ml polymer dose are the lowest and the filtrate rates of the 30 ml polymer dose are the highest. For the 10 ml dose, the filtrate rate of 137.8 kPa (20 psi) condition is the highest; the other two conditions have nearly the same filtrate rates. For the 20 ml and 30 ml polymer dosages, 68.9 kPa (10 psi) conditions have the highest filtrate rates. The 20 ml polymer dose at 103.4 kPa (15 psi) has lower filtrate rate than the raw sludge sample.

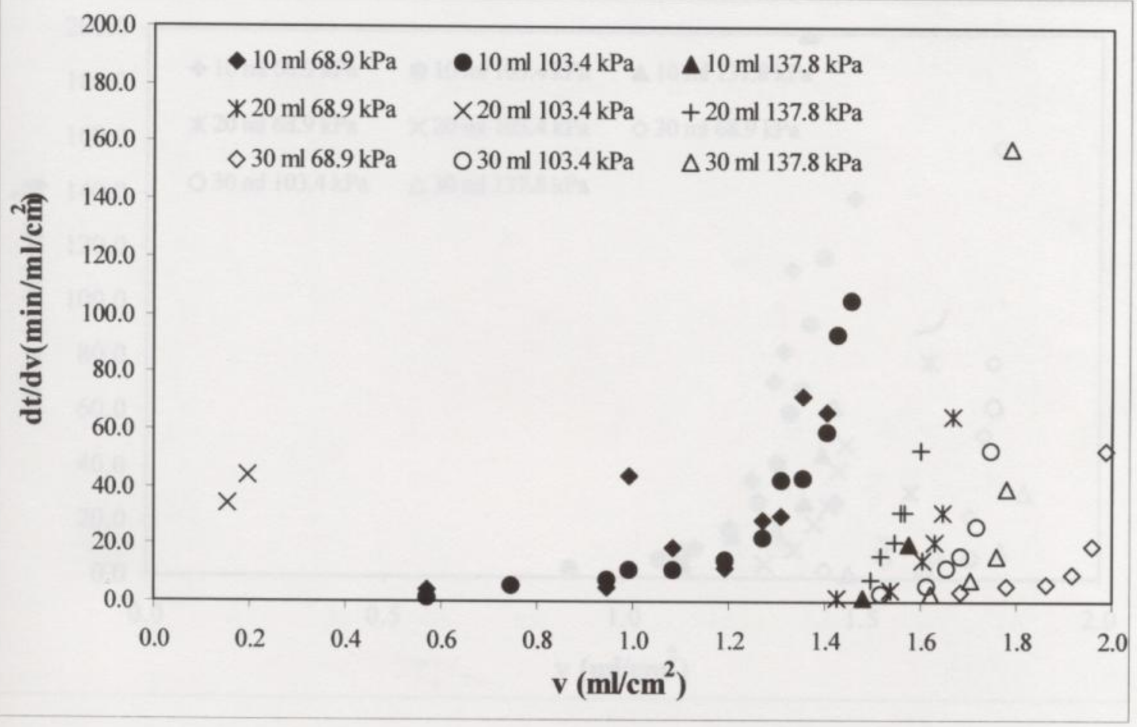

Figure 4-12 *dt/dv* Versus Filtrate Volume with 0.5 % Polymer

Figure 4-13 is a plot of *dt/dv* versus *v* with 1 % polymer at three different pressures. The polymer dosages are 10 ml, 20 ml and 30 ml. As shown in the graph, the specific resistances of each curve increases with *v*, as the filtrate rates decrease. Each filtrate rate is higher than the filtrate rate of the raw sludge sample for all conditions. The specific resistances of the 10 ml dose are the highest and the specific resistances of the 30 ml dose are the lowest. The filtrate rates of the 10 ml dose are the lowest and the filtrate rates for 30 ml dose are the highest. For the 10 ml and 30 ml dosages, 137.8 kPa (20 psi) pressure condition has the highest filtrate rate and 68.9 kPa (10 psi) has the lowest filtrate rate. For the 20 ml dose, 68.9 kPa (10 psi) has a higher filtrate rate than the 103.4 kPa (15 psi) condition.

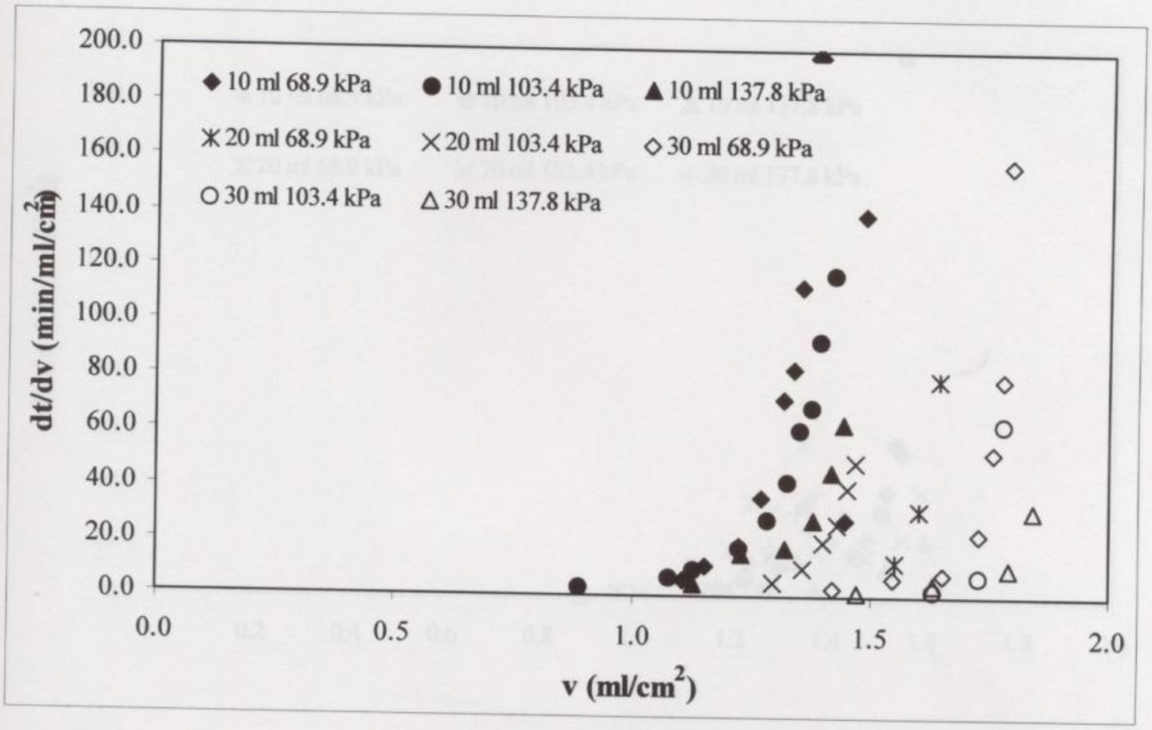

Figure 4-13 *dt/dv* Versus Filtrate Volume with 1 % Polymer

Figure 4-14 is a plot of *dt/dv* versus *v*, using two different dosages of 2 % polymer at three applied pressures. For 2 % polymer, the 30 ml dose experiments could not be performed, since all the sludge particles passed through the filter medium. The specific resistances of the 20 ml dose are higher and the filtrate rates of the 20 ml dose are lower than those of the 10 ml dose at the same filtration pressures. The specific resistances increase with *v*, and the filtrate rates decrease, for all conditions. For the 10 ml dose, the filtrate rate of the 137.8 kPa (20 psi) condition is the highest, while the filtrate rates of the 68.9 kPa (10 psi) and 103.4 kPa (15 psi) are nearly the same. For the 20 ml polymer dose, the filtrate rate of 103.4 kPa (15 psi) is the highest and the the filtrate rate of the 68.9 kPa (10 psi) condition is the lowest.

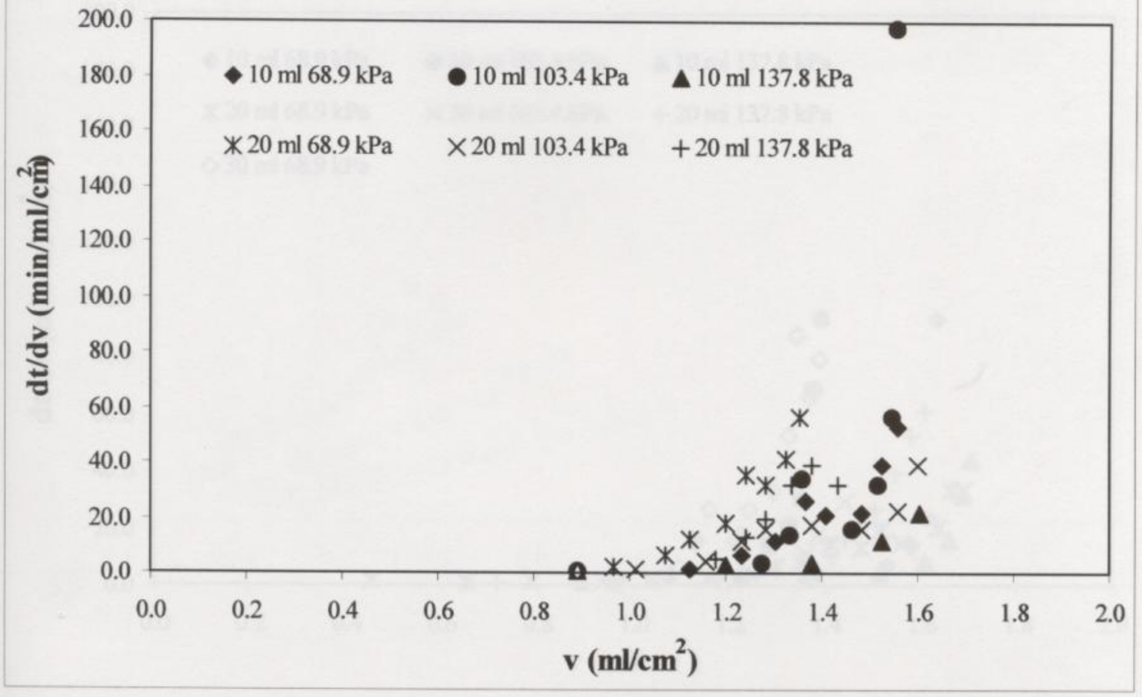

Figure 4-14 *dt/dv* Versus Filtrate Volume with 2 % Polymer

Figure 4-15 is a plot of *dt/dv* versus *v* with three different dosages of 3 % polymer at different pressures. The specific resistances of all conditions increase with *v*, while the filtrate rates decrease with *v*. The filtrate rate of the 30 ml dose at 68.9 kPa (10 psi) is the lowest and the filtrate rate of the 10 ml dose at 137.8 kPa (20 psi) is the highest. For the 10 ml dose, the pressure condition of 103.4 kPa (15 psi) has the lowest filtrate rate and that of 137.8 kPa (20 psi) has the highest filtrate rate. For the 20 ml polymer dose, the pressure condition of 137.8 kPa (20 psi) has the lowest filtrate rate and that of the pressure of 103.4 kPa (15 psi) is the highest. For the 30 ml dose, the experiment could only be performed at 68.9 kPa (10 psi); for the other two pressures, all the sludge particles passed through the filter medium.

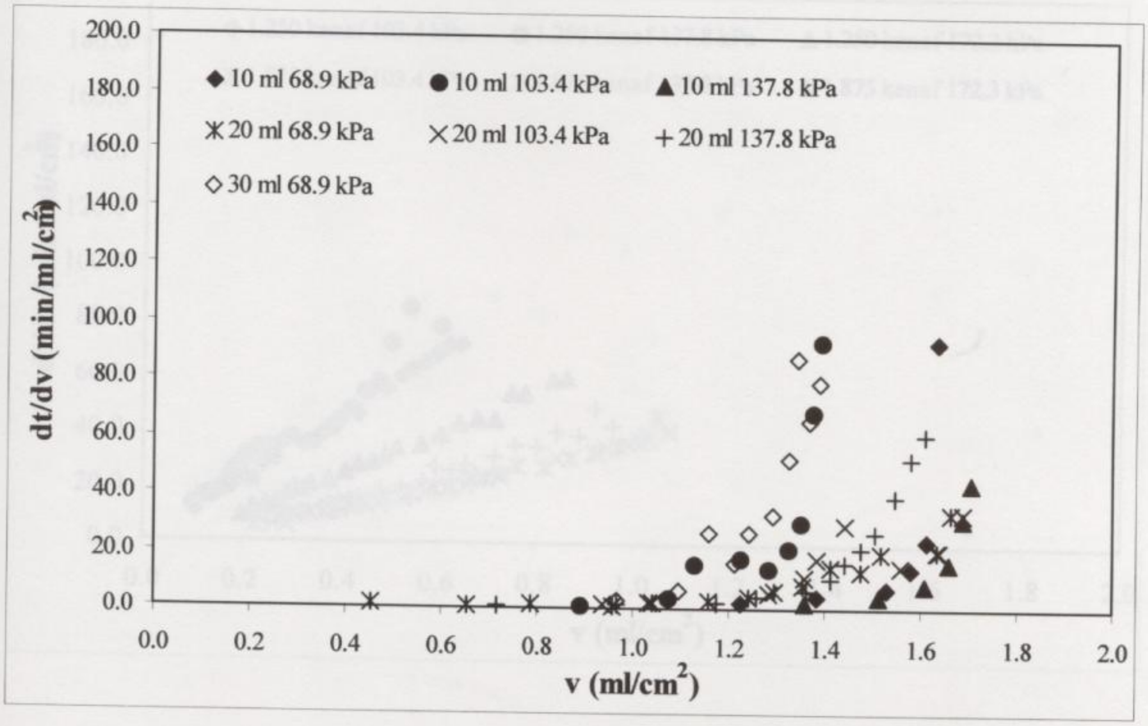

Figure 4-15 *dt/dv* Versus Filtrate Volume with 3 % Polymer

Figure 4-16 is a plot of *dt/dv* versus *v* with three different dosages of 500 μm kenaf at three different filtration pressures. In the figure, 1.250 and 1.875 are the weight fractions of kenaf to the dry solids weight in the raw sludge sample. The specific resistances are nearly constant for all filtration conditions, and the filtrate rates decrease with *v*. The specific resistances of the 1.250 kenaf fraction are higher than those of the 1.875 kenaf weight fraction. For the 1.250 kenaf weight fraction, 172.3 kPa (25 psi) has the highest filtrate rates and other two pressure conditions have the nearly same filtrate rate. For the 1.875 kenaf fraction, 103.4 kPa (15 psi) has the lowest filtrate rate and the other two pressure conditions have nearly the same filtrate rates.

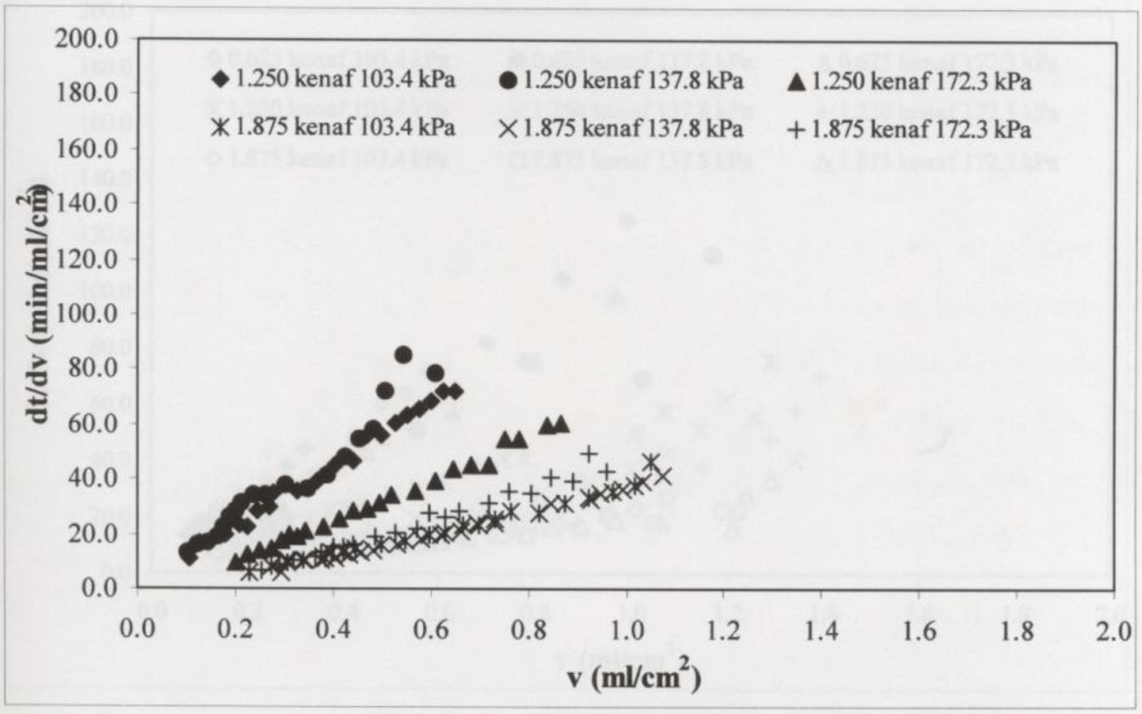

Figure 4-16 *dt/dv* Versus Filtrate Volume with 500 μm Kenaf

Figure 4-17 is a plot of *dt/dv* versus *v* with various dosages of 1000 μm kenaf at three different filtration pressures. The specific resistances do not change with *v* for the 0.625 kenaf weight fractions, but they increase with *v* for the 1.250 and 1.875 weight fractions after *v* is 1.0 ml/cm^2. Filtrate rates increase with *v* for all conditions. For the 0.625 kenaf fraction, 103.4 kPa (15 psi) has the lowest filtrate rate and other two pressure conditions have nearly the same filtrate rates. For the 1.250 kenaf weight fraction, 172.3 kPa (25 psi) has the highest filtrate rate and the 103.4 kPa (15 psi) has the lowest filtrate rate. For the 1.875 kenaf fraction, all the three conditions have nearly the same filtrate rates.

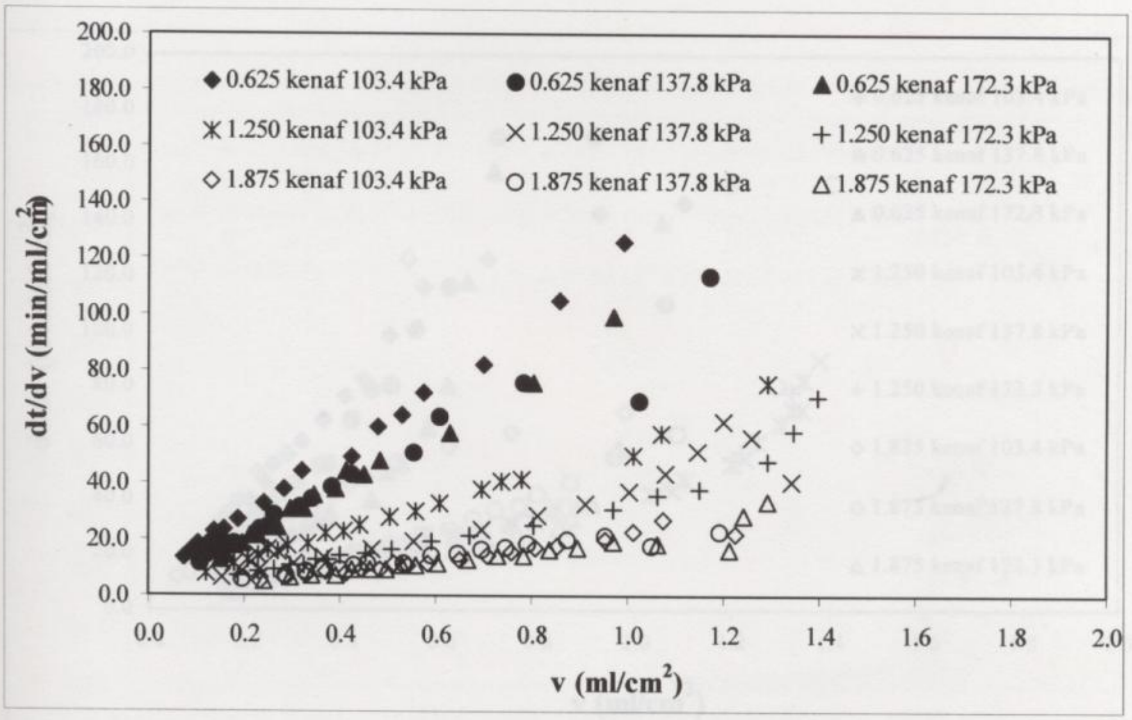

Figure 4-17 *dt/dv* Versus Filtrate Volume with 1000 μm kenaf

Figure 4-18 is a plot of *dt/dv* versus *v* with three dosages of 1500 μm kenaf at three different pressures. The specific resistances of the 0.625 kenaf weight fraction are the highest and the specific resistances of the 1.250 kenaf fraction are the lowest. The filtrate rates of the 0.625 kenaf fraction are the lowest and those of the 1.250 kenaf fraction are the highest. For the 0.625 kenaf fraction, 103.4 kPa (15 psi) has the lowest filtrate rate and 172.3 kPa (25 psi) has the highest filtrate rate. For the 1.250 kenaf fraction, all the pressure conditions have nearly the same filtrate rates. For the 1.875 kenaf weight fraction, 103.4 kPa (15 psi) has the lowest filtrate rate and 172.3 kPa (25 psi) has the highest filtrate rate.

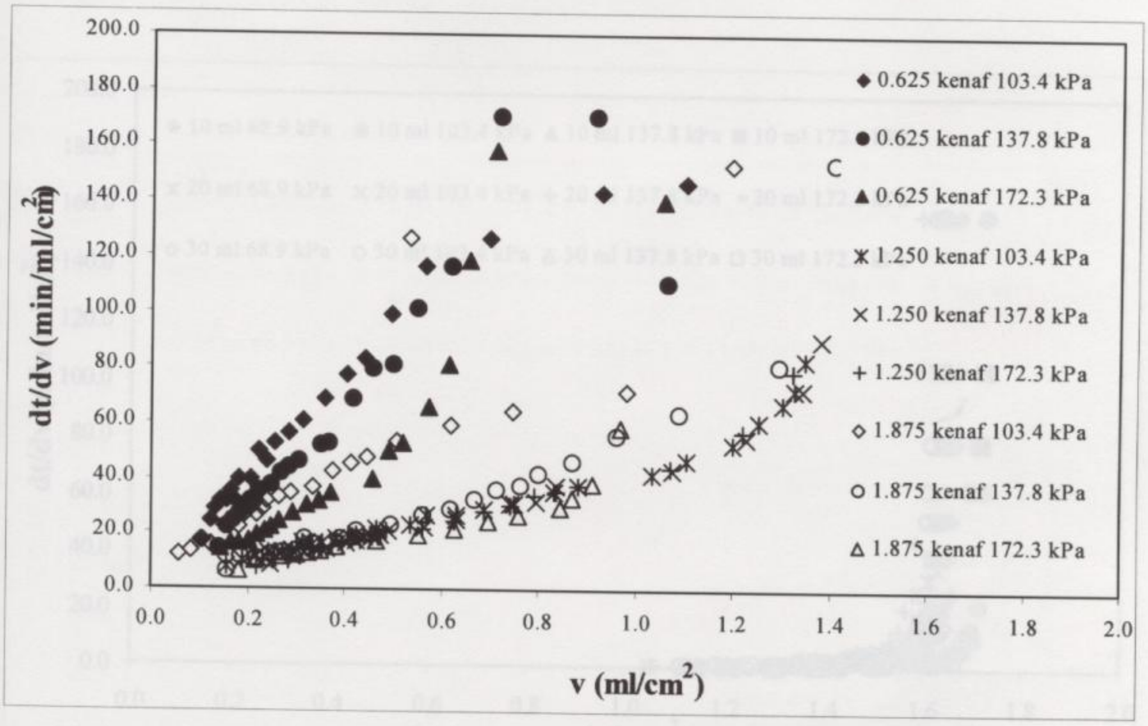

Figure 4-18 *dt/dv* Versus Filtrate Volume with 1500 μm Kenaf

Figure 4-19 is a plot of *dt/dv* versus *v* with different dosages of 1 % polymer and 0.625 weight fraction of 1000 μm kenaf at four different pressure conditions. The specific resistances of all the conditions increase with filtrate volume per unit filter area and the filtrate rates decrease with *v*. The filtrate rates of all the conditions are nearly the same and specific resistances remain constant until *v* is 1.5 ml/cm^2. Beyond 1.5 ml/cm^2, the filtrate rates of all conditions dramatically decrease with *v* and specific resistances dramatically increase with *v*. The 20 ml polymer dose at 137.8 kPa (20 psi) has the lowest filtrate rate and the 10 ml polymer dose at 103.4 kPa (15 psi) has the highest filtrate rate. In this figure, the 10 ml polymer dose has better filtrate rates than the other two polymer dosage conditions.

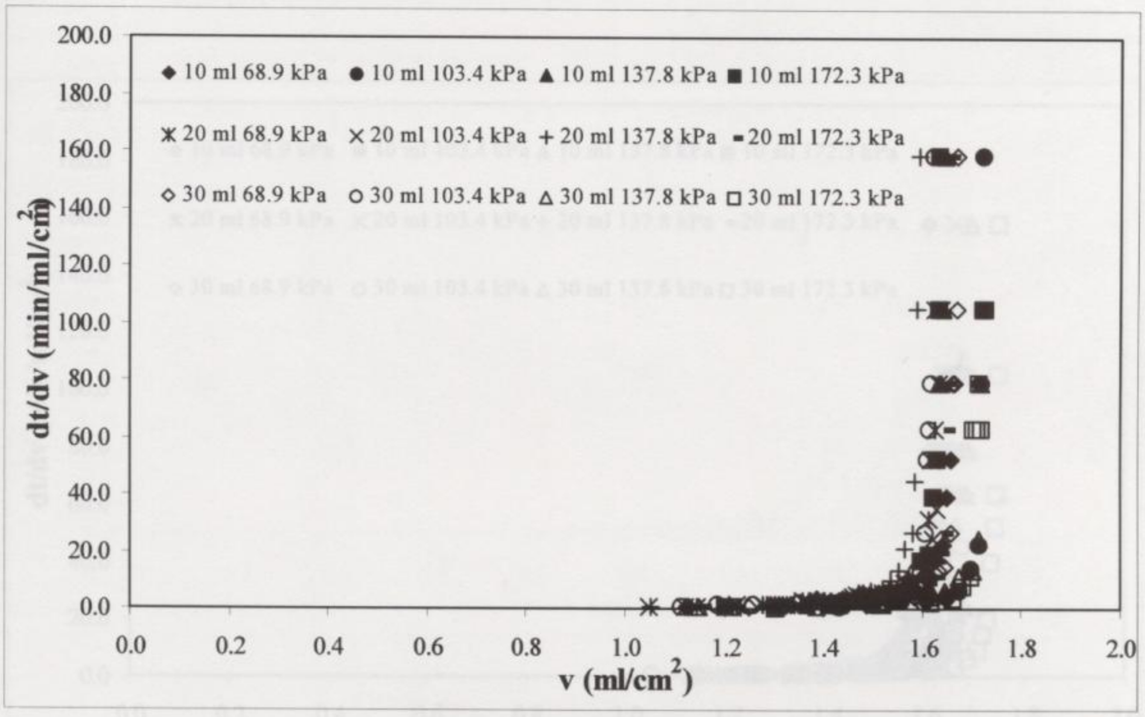

Figure 4-19 *dt/dv* Versus Filtrate Volume with 0.625 Kenaf Fraction and Polymer

Figure 4-20 is a plot of *dt/dv* versus *v* with three different dosages of 1 % polymer and 1.250 weight fraction of 1000 μm kenaf at four different pressures. The specific resistances increase with *v* and the filtrate rates decrease with *v* for all the conditions. The dosage of 10 ml polymer has the lowest filtrate rates and highest specific resistances, while the dosage of 30 ml polymer has the highest filtrate rates and lowest specific resistances. For the 10 ml polymer dose, the pressures of 68.9 kPa (10 psi) and 103.4 kPa (15 psi) have nearly the same filtrate rates; the pressures of 137.8 kPa (20 psi) and 172.3 kPa (25 psi) have the same filtrate rates. Filtrate rates of 68.9 kPa (10 psi) and 103.4 kPa (15 psi) are higher than those of 137.8 kPa (20 psi) and 172.3 kPa (25 psi). For the 20 ml dose, the filtrate rates of all conditions are nearly the same. For the 30 ml dose, the condition of 172.3 kPa (25 psi) has the highest filtrate rate.

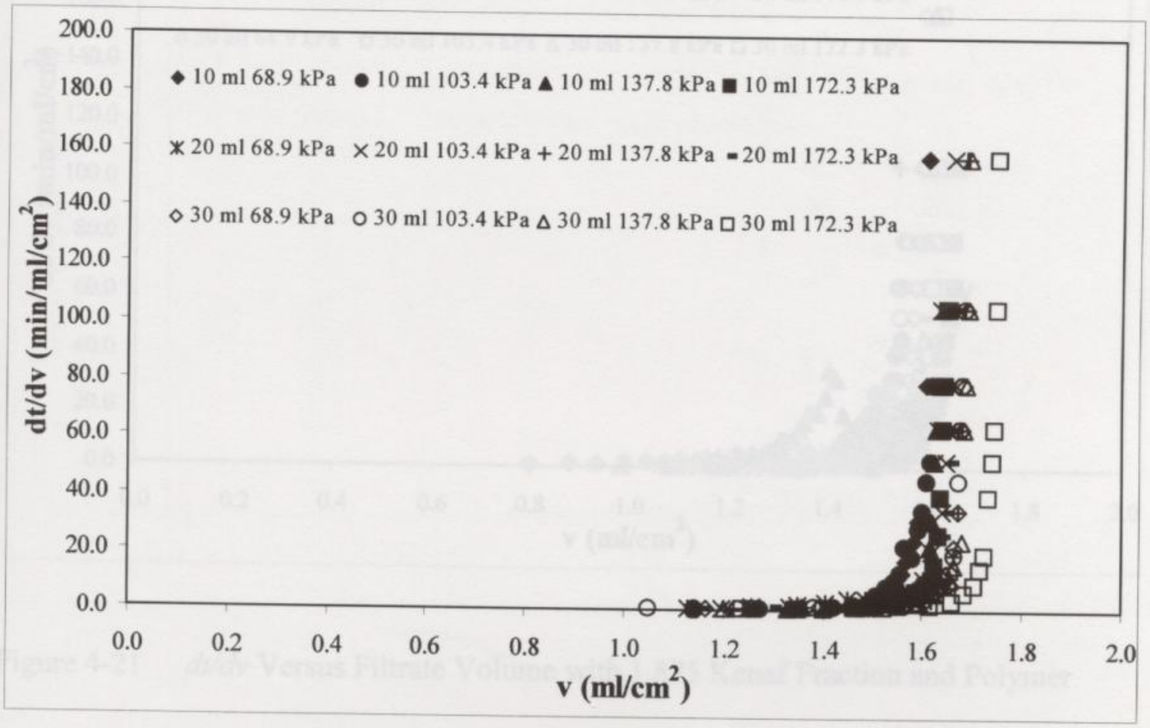

Figure 4-20 *dt/dv* Versus Filtrate Volume with 1.250 Kenaf Fraction and Polymer

Figure 4-21 is a plot of *dt/dv* versus *v* with the 1.875 weight fraction of 1000 μm kenaf and three different dosages of 1 % polymer at four different pressures. The specific resistances increase with *v* and filtrate rates decrease with *v* for all conditions. The 10 ml polymer dose at 137.8 kPa (20 psi) has the lowest filtrate rate and the highest specific resistance; the 10 ml polymer dose at 172.3 kPa (25 psi) has the highest filtrate rate. The polymer dosage of 20 ml has lower filtrate rates than the 30 ml polymer dose. For the 20 ml dose, 172.3 kPa (25 psi) has the lowest filtrate rate and 103.4 kPa (15 psi) has the highest filtrate rate. For the 30 ml polymer dose, 103.4 kPa (15 psi) has the lowest filtrate rate, and 137.8 kPa (20 psi) and 172.3 kPa (25 psi) have the highest filtrate rates.

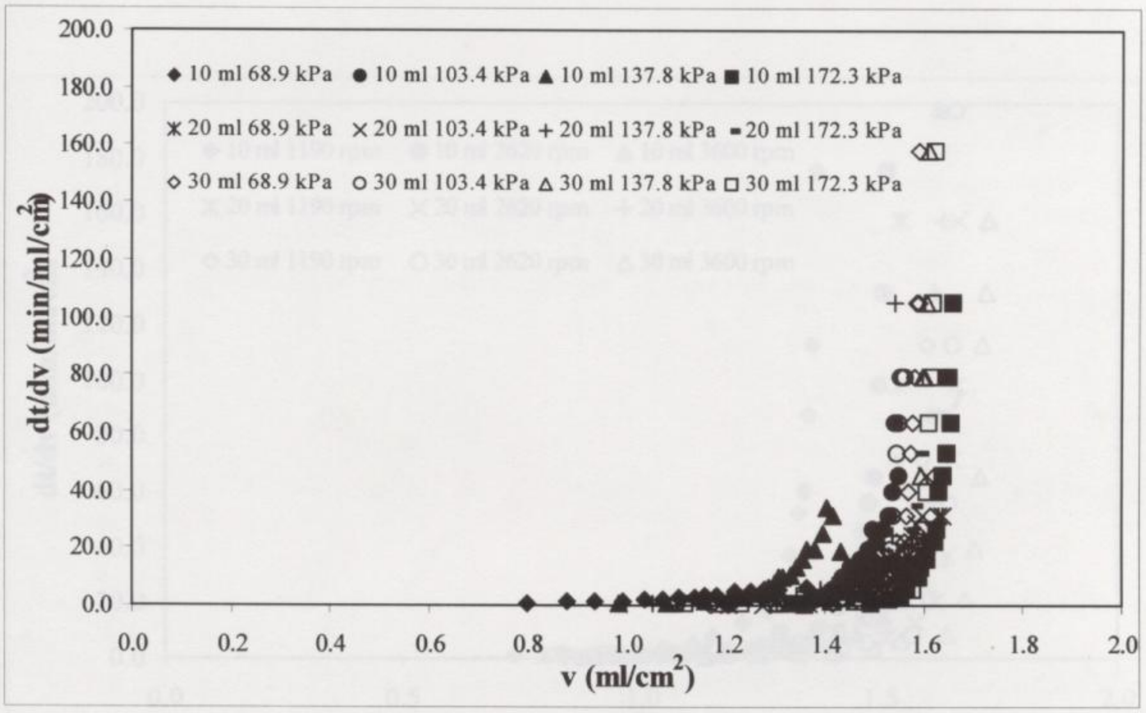

Figure 4-21 *dt/dv* Versus Filtrate Volume with 1.875 Kenaf Fraction and Polymer

4-4 CENTRATE RATES

Figure 4-22 is a plot of *dt/dv* versus centrate volume per unit area with three different dosages of 0.5 % polymer at various rotational speeds. The centrate rates decrease with *v* for all conditions. The dosages of 10 ml polymer have the lowest centrate rates and the dosages of 30 ml have the highest centrate rates. For the 10 ml dose, 3600 rpm has the highest centrate rate and 1190 rpm has the lowest centrate rate. For the 20 ml polymer dose, 1190 rpm has the lowest centrate rate and 2620 rpm has the highest centrate rate. For the 30 ml dose, 1190 rpm has the lowest centrate rate and 3600 rpm has the highest centrate rate.

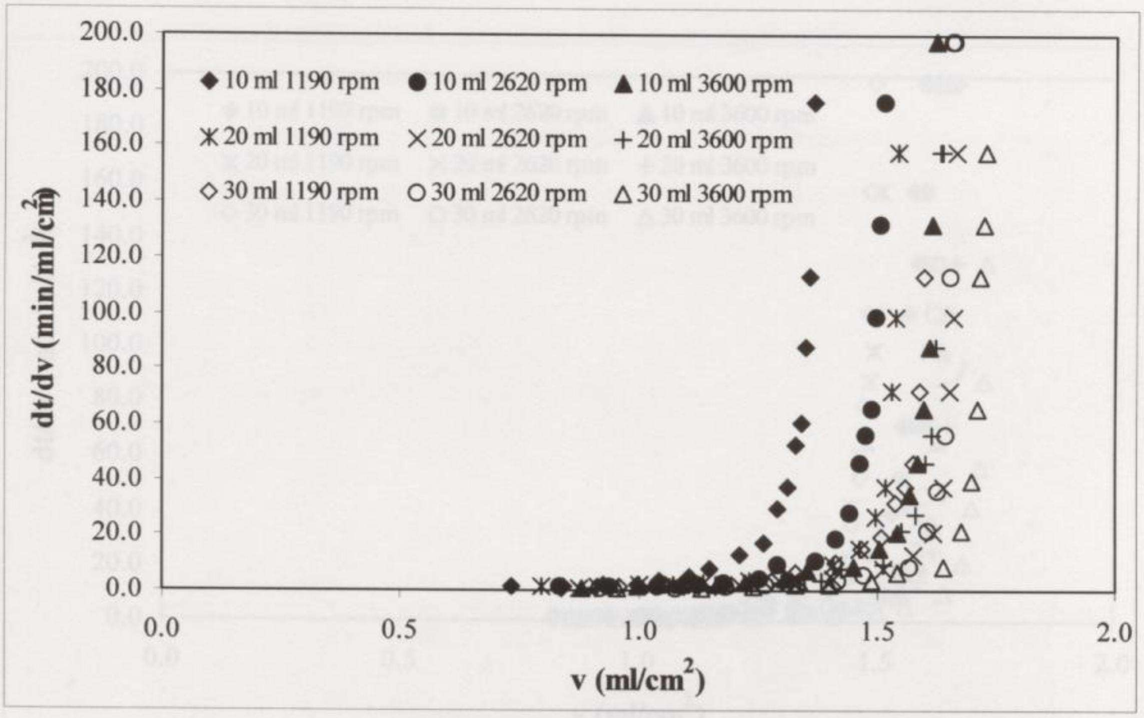

Figure 4-22 *dt/dv* Versus Centrate Volume with 0.5 % Polymer

Figure 4-23 is a plot of *dt/dv* versus centrate volume per unit area with three different dosages of 1 % polymer at three different rotational speeds. The centrate rates increase as the rotational speeds increase. For 1190 rpm, the 20 ml and 30 ml dosages either have nearly the same centrate rates as, or lower centrate rates than the 10 ml polymer dose. For 2620 rpm, the centrate rates of the 20 ml and 30 ml dosages are nearly the same and a little higher than that of the dosage of 10 ml. For 3600 rpm, the 30 ml dose has the highest centrate rate for all *v*, and the dosages of the 10 ml and 20 ml polymer have nearly the same centrate rates before 1.5 ml/cm^2 of *v*. The dosage of 20 ml has a slightly higher centrate rate than the 10 ml dose after 1.5 ml/cm^2 of *v*. The centrate rates decrease as *v* increase.

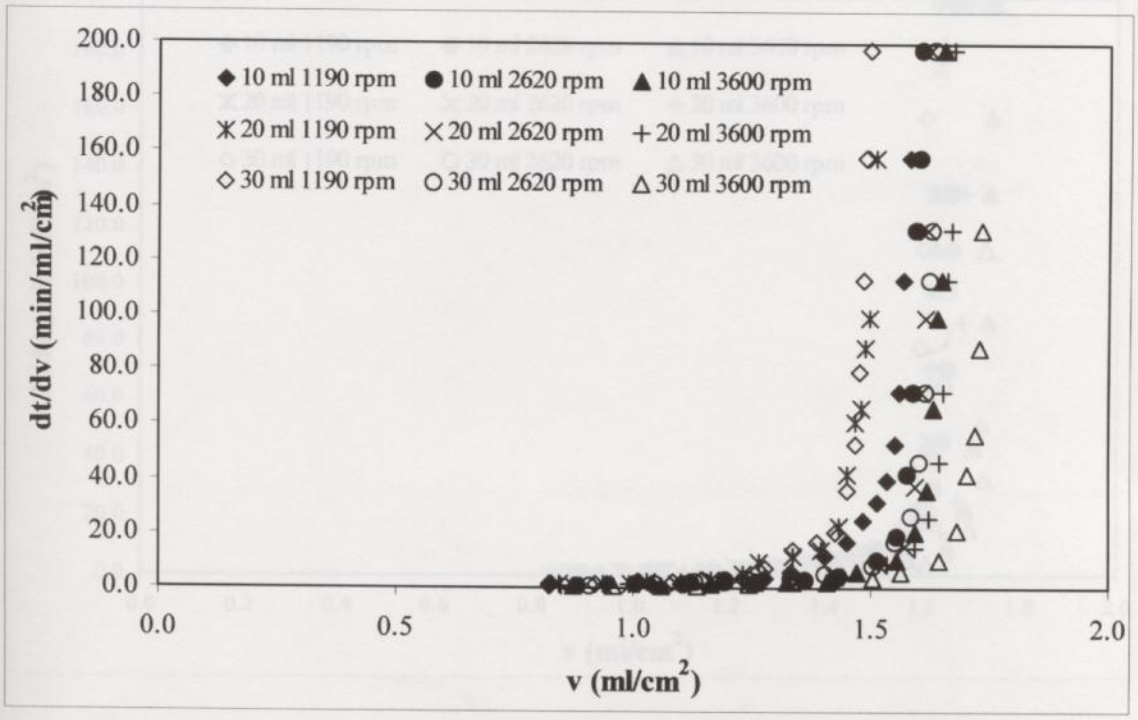

Figure 4-23 *dt/dv* Versus Centrate Volume with 1 % Polymer

Figure 4-24 is a plot of *dt/dv* versus centrate volume per unit area with three dosages of 2 % polymer at three different rotational speeds. The centrate rates decrease as *v* increases, after 1.5 ml/cm^2 of *v,* the centrate rates dramatically decrease with *v*. Centrate rates increase as rotational speeds increase. The condition of the 30 ml dose at 1190 rpm has the lowest centrate rate and the condition of the 30 ml dose at 3600 rpm has the highest centrate rate. For 1190 rpm, the 30 ml dose has a little lower centrate rate than the dosages of 10 ml and 20 ml, and the dosages of 10 ml and 20 ml have nearly the same centrate rates. For 2620 rpm, the dosages of 10 ml and 30 ml have the same centrate rates and both of which are higher than that of the dosage of 20 ml. For 3600 rpm, the 20 ml dose has the lowest centrate rate, while the 30 ml dose has the highest centrate rate.

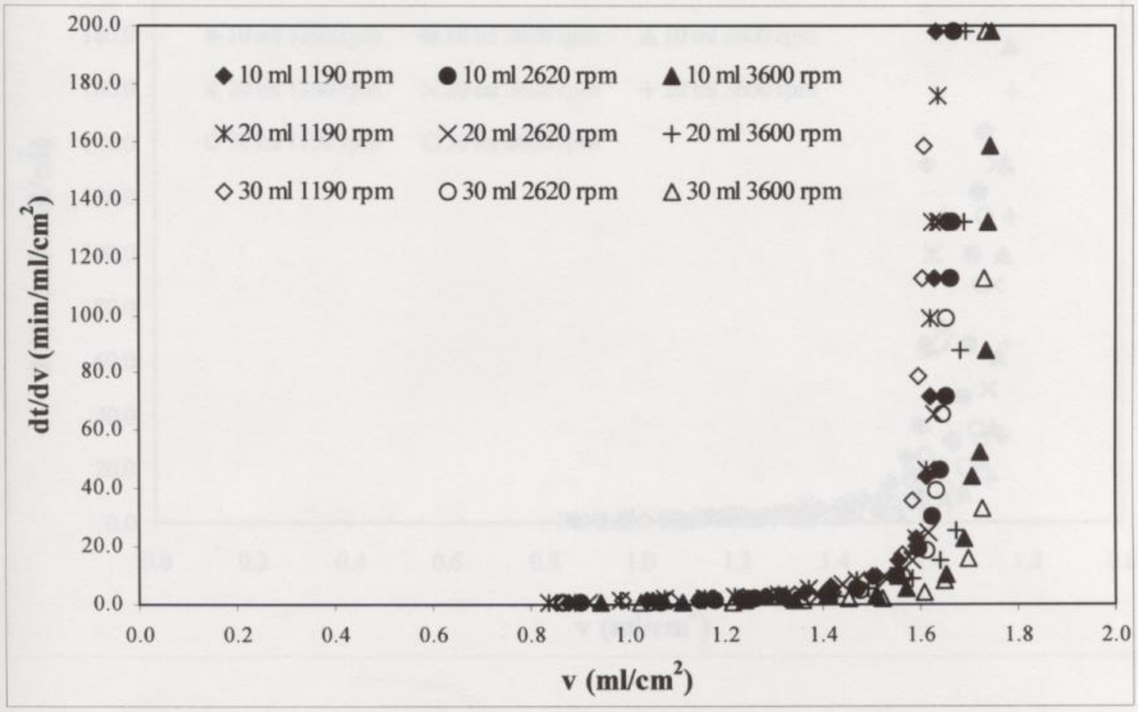

Figure 4-24 *dt/dv* Versus Centrate Volume with 2 % Polymer

Figure 4-25 is a plot of *dt/dv* versus centrate volume per unit area with various dosages of 3 % polymer at three rotational speeds. As shown in the figure, the centrate rates increase with *v*. Centrate rates increase as rotational speeds increase. For 1190 rpm, the 30 ml dose has the highest centrate rate and the dosage of 10 ml polymer has the lowest centrate rate. For 2620 rpm, the 20 ml polymer dose has the highest centrate rate and the dosage of 10 ml polymer has the lowest centrate rate. For 3600 rpm, it was not possible to obtain data for the condition of the 30 ml dose because too many sludge particles passed through the centrifuge. The dosages of 10 ml and 20 ml polymer have nearly the same centrate rate for all *v*.

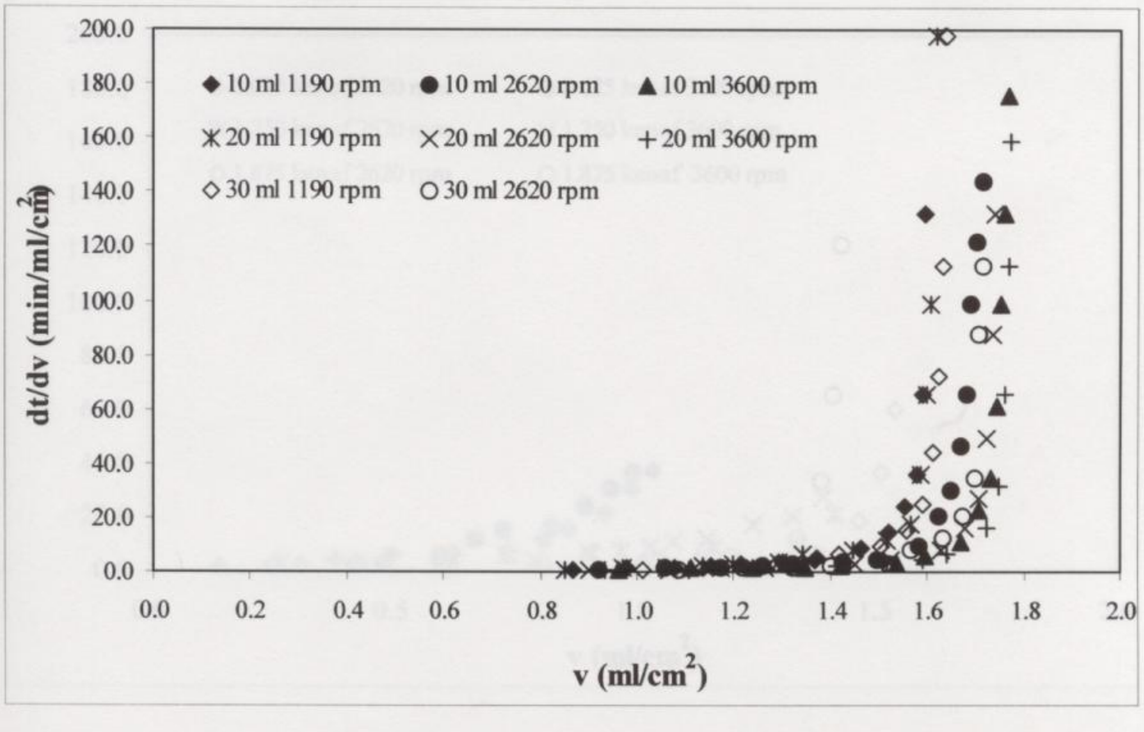

Figure 4-25 *dt/dv* Versus Centrate Volume with 3 % Polymer

Figure 4-26 is a plot of *dt/dv* versus centrate volume per unit area with various dosages of 500 μm kenaf at two different rotational speeds. The 0.625 kenaf weight fraction has the lowest centrate rates while the 1.875 kenaf weight fraction has the highest centrate rates. Centrate rates increase as rotational speeds decrease for all conditions. For 2620 rpm, the 0.625 kenaf weight fraction has the lowest centrate rate and the 1.875 kenaf weight fraction has the highest centrate rate. For 3600 rpm, the 0.625 kenaf weight fraction has the lowest centrate rate and the 1.875 kenaf weight fraction has the highest centrate rate before 1.4 ml/cm^2 of *v*; after 1.4 ml/cm^2 of *v*, the 1.250 kenaf weight fraction has the highest centrate rate for 3600 rpm.

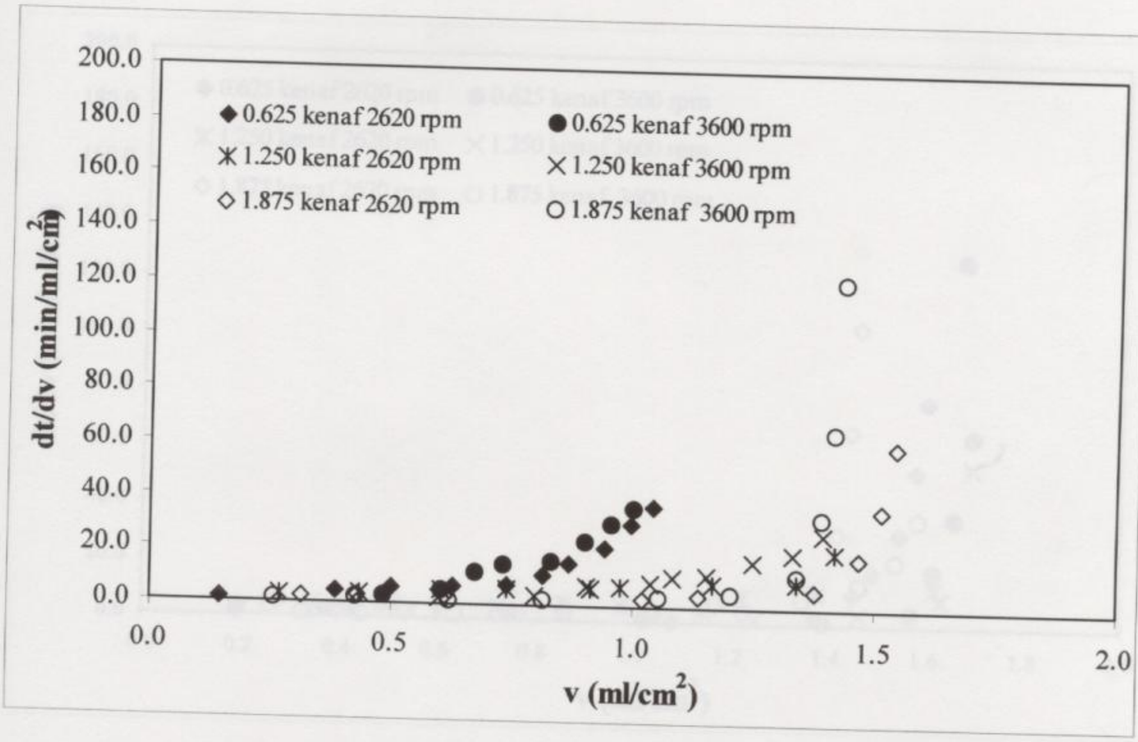

Figure 4-26 *dt/dv* Versus Centrate Volume with 500 μm Kenaf

Figure 4-27 is a plot of *dt/dv* versus centrate volume per unit area with three different dosages of 1000 μm kenaf at two different rotational speeds. Centrate rates decrease with *v* for all conditions. Until *v* is 1.4 ml/cm^2, the centrate rates of all conditions are nearly the same and do not change too much. After 1.4 ml/cm^2 of *v*, the 1.875 kenaf weight fraction at 2620 rpm has the lowest centrate rate and the 1.250 kenaf weight fraction at 3600 rpm has the highest centrate rate. For 2620 rpm, the 1.875 kenaf weight fraction has the lowest centrate rate and the 1.250 weight fraction has the highest centrate rate. For 3600 rpm, the 1.875 weight fraction has the lowest centrate rate and the 1.250 kenaf weight fraction has the highest centrate rate.

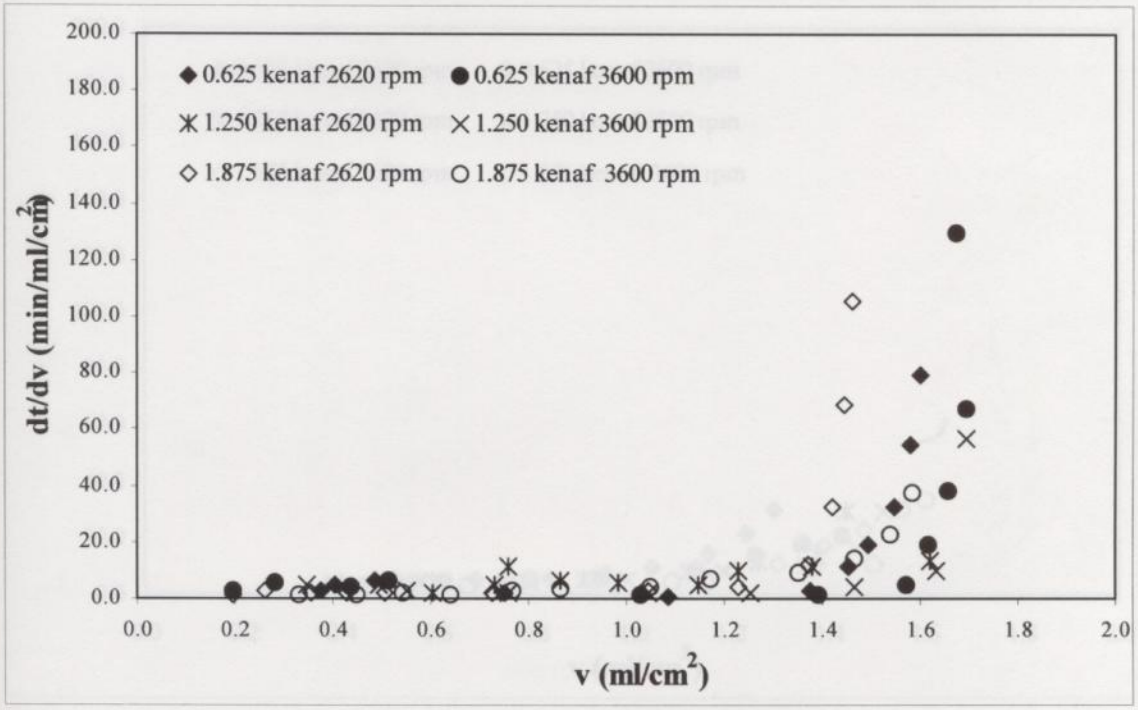

Figure 4-27 *dt/dv* Versus Centrate Volume with 1000 μm Kenaf

Figure 4-28 is a plot of *dt/dv* versus centrate volume per unit area with three different dosages of 1500 μm kenaf at 2620 rpm and 3600 rpm. For all conditions, centrate rates decrease with increasing *v*. The 0.625 kenaf weight fraction has the lowest centrate rates and the 1.875 weight fraction has the highest centrate rates. As the rotational speeds increase, centrate rates increase. For 2620 rpm, the 0.625 kenaf weight fraction has the lowest centrate rate and the 1.250 weight fraction has the highest centrate rate. For 3600 rpm, the 0.625 kenaf weight fraction has the lowest centrate rate and the 1.875 kenaf weight fraction has the highest centrate rate.

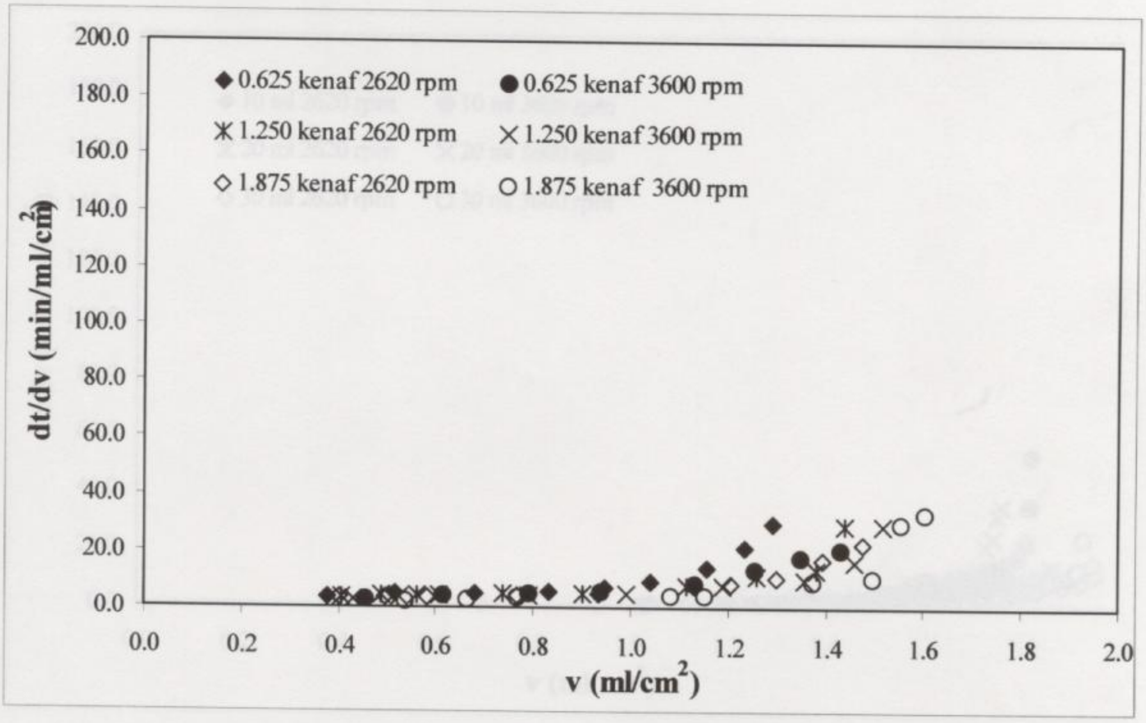

Figure 4-28 *dt/dv* Versus Centrate Volume with 1500 μm Kenaf

Figure 4-29 is a plot of *dt/dv* versus centrate volume per unit area with the 0.625 weight fraction of 1000 μm kenaf and three different dosages of 1 % polymer at 2620 rpm and 3600 rpm. All the centrate rates decrease as *v* increases. The 20 ml dose at 3600 rpm has the lowest centrate rate after *v* is 1.6 ml/cm^2. The 30 ml dose at 2620 rpm has the highest centrate rate. The centrate rates of 2620 rpm are higher than the centrate rates of 3600 rpm. For 2620 rpm, the 10 ml polymer dose has the lowest centrate rate and the 30 ml dose has the highest centrate rate. For 3600 rpm, the 20 ml dose has the lowest centrate rate and the 30 ml dose has the highest centrate rate.

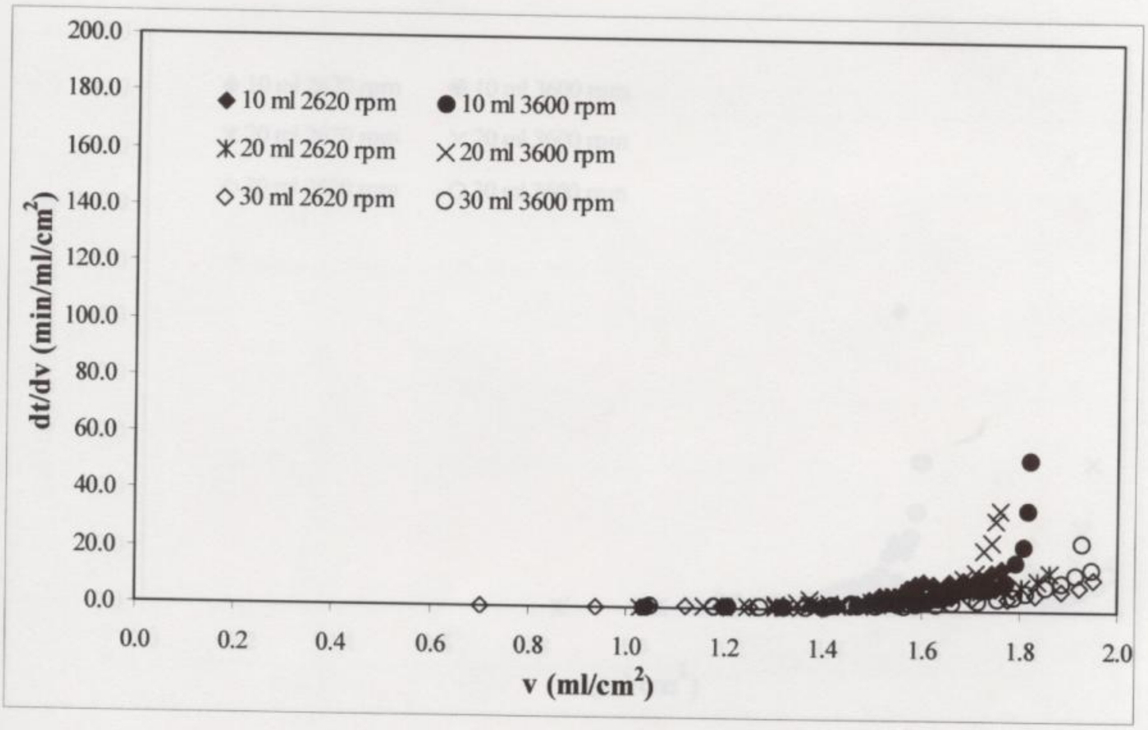

Figure 4-29 *dt/dv* Versus Centrate Volume with 0.625 Kenaf Fraction and Polymer

Figure 4-30 is a plot of *dt/dv* versus centrate volume per unit area with the 1.250 weight fraction of 1000 μm kenaf and three different dosages of 1 % polymer at 2620 rpm and 3600 rpm. All the centrate rates decrease with *v*. The dosage of 10 ml polymer has the lowest centrate rates and the dosage of 30 ml has the highest centrate rates. The centrate rates of 3600 rpm are higher than the centrate rates of 2620 rpm. For 2620 rpm, the 10 ml polymer dose has the lowest centrate rate and the 20 ml dose has the highest centrate rate. For 3600 rpm, the 10 ml dose has the lowest centrate rate and the dosage of 30 ml polymer has the highest centrate rate.

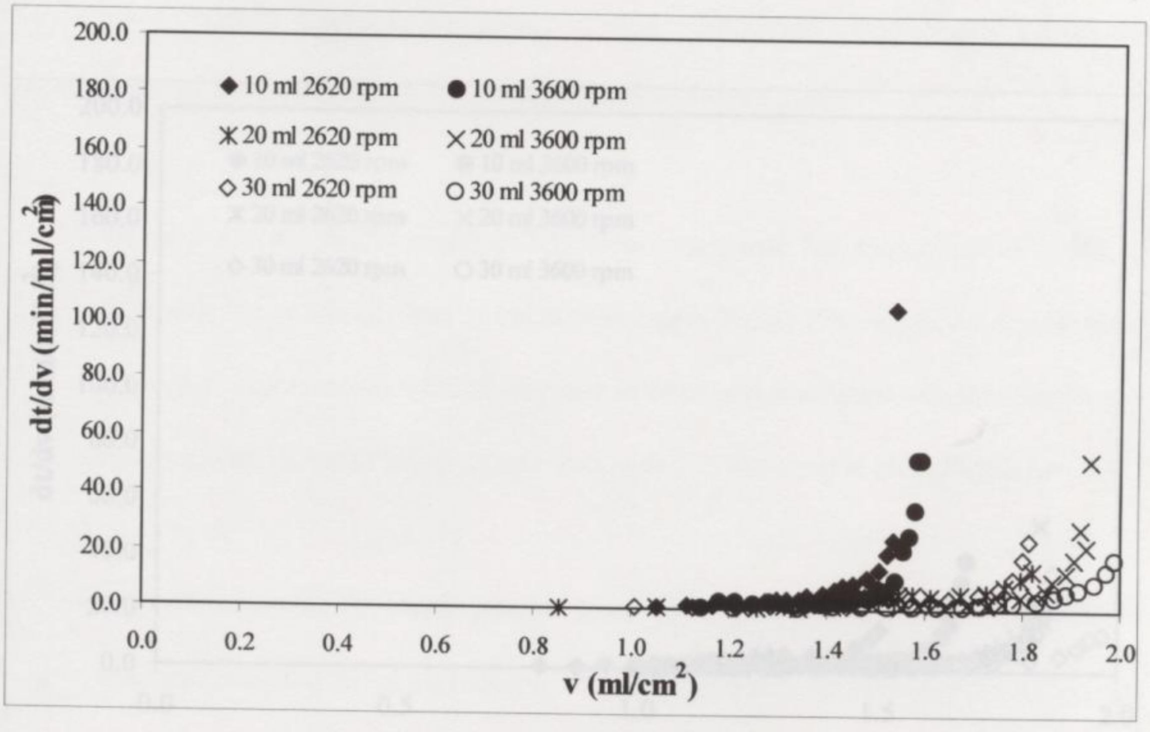

Figure 4-30 *dt/dv* Versus Centrate Volume with 1.250 Kenaf Fraction and Polymer

Figure 4-31 is a plot of *dt/dv* versus centrate volume per unit area with the 1.875 weight fraction of 1000 μm kenaf and three different dosages of 1 % polymer at 2620 rpm and 3600 rpm. All the centrate rates decrease with *v*. The 10 ml polymer dose at 2620 rpm has the lowest centrate rates and the 30 ml dose at 2620 rpm has the highest centrate rates. For the 10 ml dose, 3600 rpm has a higher centrate rate than 2620 rpm. For the dosages of 20 ml and 30 ml polymer, the centrate rates of 2620 rpm are higher than the centrate rates of 3600 rpm. For 2620 rpm, the 10 ml dose has the lowest centrate rate and the 30 ml dose has the highest centrate rate. For 3600 rpm, the 10 ml dose has the lowest centrate rate and the 30 ml dose has the highest centrate rate.

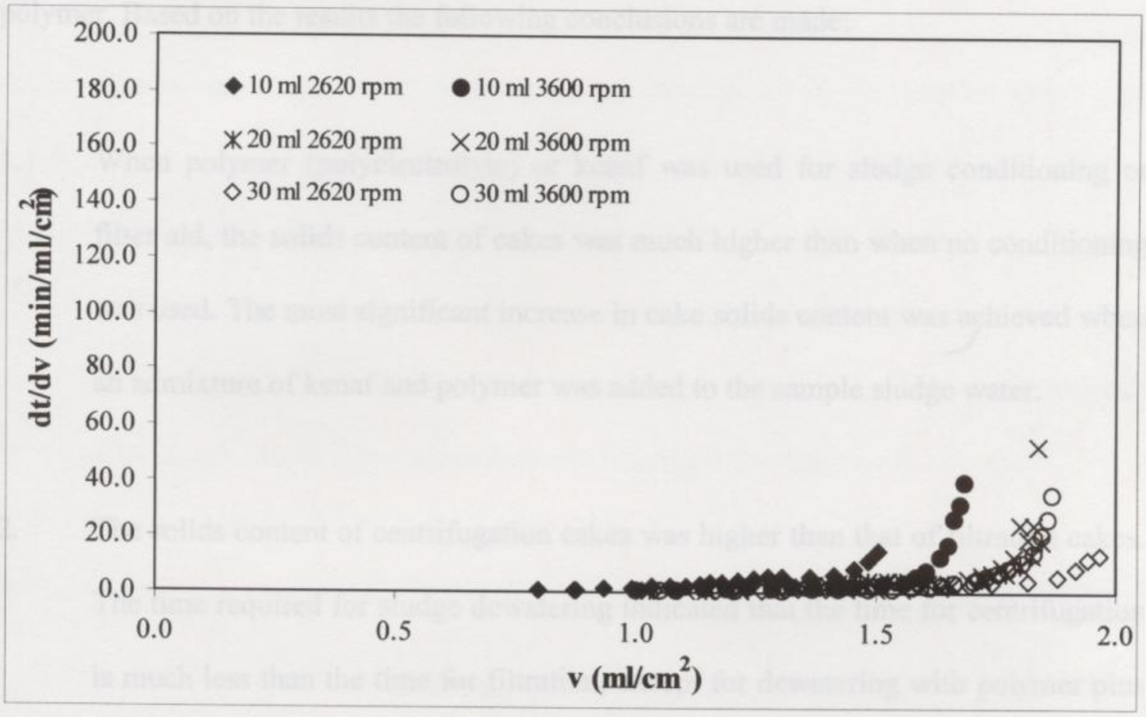

Figure 4-31 *dt/dv* Versus Centrate Volume with 1.875 Kenaf Fraction and Polymer

CHAPTER 5

SUMMARY AND CONCLUSIONS

Solid-liquid separation is one of the essential processes in many wastewater treatment and industrial plants. Filtration and centrifugation are important operations in solid-liquid separation.

To improve the treatment of the municipal wastewater, this research has conducted laboratory filtration and centrifugation with kenaf, polymer and kenaf plus polymer. Based on the results the following conclusions are made:

1. When polymer (polyelectrolyte) or kenaf was used for sludge conditioning or filter aid, the solids content of cakes was much higher than when no conditioning was used. The most significant increase in cake solids content was achieved when an admixture of kenaf and polymer was added to the sample sludge water.

2. The solids content of centrifugation cakes was higher than that of filtration cakes. The time required for sludge dewatering indicated that the time for centrifugation is much less than the time for filtration, except for dewatering with polymer plus kenaf. The average time for centrifugation was 600 sec for polymer or kenaf and

200 sec for polymer plus kenaf. The average filtration time for polymer or kenaf was 1200 sec and the filtration time with polymer plus kenaf was 200 sec.

3. Kenaf increased the energy content of sludge cakes. The energy content of kenaf was 16.3 MJ/kg (7000 Btu/lb) when the dosage of kenaf was 7.5 g, and the energy content of raw sludge cake without kenaf was 13.9 MJ/kg (6000 Btu/lb). The energy content of cakes, which had 2.5 g dosages, were 15.8 MJ/kg (6800 Btu/lb), for 5 g dosage the energy content was 16 MJ/kg (6900 Btu/lb). If the solid content of sludge cake is sufficiently high (over 21 % wt/wt), the cakes can be combusted in a incinerator, which reduces of the volume of final disposal of sludge and increases the energy recovery from the sludge cakes.

4. The centrate rates were higher than filtrate rates and the rates of kenaf plus polymer experiments were higher than the other two conditioning groups. When polymer was added as a conditioner for centrifugation and filtration, as rotational speeds increased, centrate rates decreased and, as filtration pressures increased, filtrate rates decreased. When kenaf was used as a filter aid, as dosages, rotational speeds and filtration pressures increased filtrate rates decreased.

5. To use kenaf and polymer together for conditioning sludge water is much better than to use kenaf or polymer alone. The polymer-kenaf blend conditioning is better in terms of solids content, filtrate and centrate rates and treatment time.

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