Application of Flocs Analysis for Coagulation Optimization at the Split Lake Water Treatment Plant

By

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

Master of Science

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ABSTRACT

The success of surface water treatment strongly depends on the effectiveness of coagulant performance. Aluminium sulfate (alum), the most widely used coagulant in water treatment plants in Canada, is well known for its poor performance in cold water. Polyaluminium chloride (PACl), a relatively new polymeric aluminium coagulant increasingly being used in water treatment plants, is found to have many advantages over conventional alum. However, PACl hydrolysis reaction is quite complex and its action is not fully understood. In this research, a series of bench-scale jar tests with alum and PACl was conducted. Alum and PACl coagulation flocs were analyzed for the evaluation of coagulant performances at 19°C and 5°C for the Split Lake water treatment plant.

The results of this research indicated that the settling properties of PACl flocs were superior to those of alum flocs, especially at the lower temperature. The average size of PACl flocs was relatively smaller than that of alum flocs. The density of PACl flocs could be higher than that of alum flocs. And the number of settled PACl flocs could be higher than that of settled alum flocs. The effects of temperature on alum flocs and PACl flocs were different. Alum flocs size decreased at 5°C. This is most likely due to the existence of monomeric aluminium species in alum aqueous solution. PACl flocs size did not change significantly at the 5°C. This may be due to the existence of Al_{13}^{7+} polymeric species in PACl aqueous solution.

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ACKNOWLEDGEMENTS

I would like to take this opportunity to express my sincere appreciation and indebtedness to my supervisor Dr. Beata Gorczyca for her valuable guidance and advice as well as her financial support throughout my graduate studies.

I would also like to thank my advisory committee members, Dr. Jan Oleszkiewicz and Dr. Nazim Cicek for their critical review and comments on my thesis.

I am extremely appreciative of Mr. Ruddy Issac, manager of the Ininew Project Management, for providing the water plant data and raw water samples. As well, I would like to acknowledge Mr. Joel Rodrigues, sales representative of Vopak Canada Ltd., who provided all chemicals for my laboratory work at no charge. This research would not have been accomplished without this support.

In addition, I would like to extend my sincere thanks to Ms. Judy Tinley for her support and help in the Environmental Engineering Lab, as well as to Ms. Judy Manness and Ms. Nicole Davie for their permission in using their Bioquant class 95 image analysis system in the Textile Laboratory.

Finally, I would like to express my special thanks to my wife Jenny Yin for all her endless help and support during my study at the University of Manitoba.

ABBREVIATIONS

ALUM	Aluminium sulfate
DOC	Dissolved organic carbon
FSD	Flocs size distribution
GCDWQ	Guidelines for Canadian Drinking Water Quality
NOM	Natural organic material
NTU	Nephelometric turbidity unit
PAC	Powdered activated carbon
PACl	Polyaluminium chloride
PSD	Particle size distribution
SPSS	Statistical Package for the Social Sciences
TCU	True color unit
WTP	Water Treatment Plant

Chapter 1 Introduction

1.1 Background

Tataskweyak Cree Nations community is located approximately 120 km northeast of Thompson, Manitoba on the northwest shore of Split Lake. Currently, about 2,000 people live there.

Tataskweyak Cree Nations community utilizes Split Lake as its drinking water source. A conventional water treatment plant (WTP) with a capacity of 14.5 L/s was built in 1987. The plant flow schematic is shown in Figure 1-1.

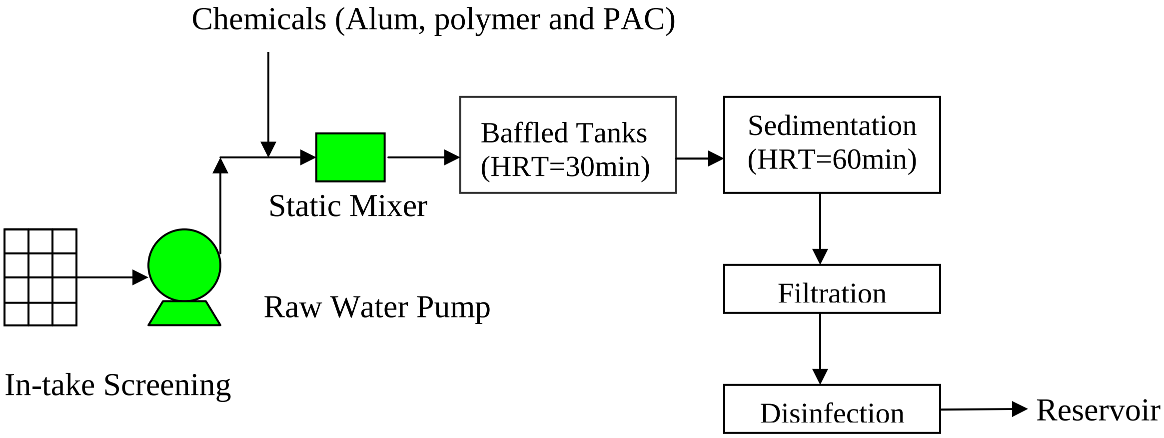

Figure 1-1 Schematic of Split Lake water treatment process

Raw water is taken from Split Lake, downstream of the Nelson and Burntwood Rivers, through a 150 m submerged intake pipe with a diameter of 150 mm. As shown in

Figure 1-1, after screening, raw water is pumped into baffled tanks where coagulation and flocculation processes occur. Alum, polymer and PAC are initially mixed with tap water in three individual stirred tanks. Then the dissolved alum, polymer and PAC are mixed with the raw water through on-line static mixers. After coagulation, the water flows to the sedimentation tanks where flocs are settled and removed from the bottom by a mechanical sludge removal apparatus. Following sedimentation, the water goes through a sand filter where the remaining lighter flocs are filtered. Finally, the treated water is chlorinated for disinfection and discharged into the storage reservoir.

The Split Lake water quality data, provided by Ininew Project Management Ltd., is presented in Table 1-1. The results indicate that turbidity and colour of the raw water exceed the Guidelines for Canadian Drinking Water Quality.

In order to analyze the variation of raw water quality, four more sample tests were conducted in 2002 and 2003. Colour and turbidity were two main parameters of concern. The test results are summarized in Table 1-2.

Table 1-1 Split Lake water quality (March 2002)

Parameters	**Raw water**	**Treated water**	**GCDWQ***
Turbidity, NTU	18.5	1	1
Colour, TCU	59	10	15
Alkalinity, mg/l	81.5	52.4	30-500
pH	7.9	7.08	6.5-8.5
Sulfate, mg/l	14.4	53	500
Nitrate + Nitrite - Nitrogen, mg/l	0.27	0.1	11
Chloride, mg/l	10.2	11	250
Total Solids, mg/l	166	152	N/A
Total Dissolved Solids, mg/l	161	151	500
Total Coliforms	200	<1	10/100ml
Fecal Coliforms	1	<1	1/100ml
DOC, mg/l	7.5	4.1	5.0
Copper, mg/l	0.009	0.004	1
Iron, mg/l	0.2	0.024	0.3
Manganese, mg/l	0.012	0.003	0.05

GCDWQ*: Guidelines for Canadian Drinking Water Quality

Table 1-2 Split Lake water quality (2002, 2003)

Parameter	**April, 02**	**August, 02**	**September, 02**	**April, 03**
Turbidity, NTU	21	44	38	22
Colour, TCU	50	70	70	50
Temperature, ºC	5	20	19	5

Table 1-2 indicates that the raw water temperature and quality changed with the season. Temperature decreased from 20ºC in August to 5ºC in April. Meanwhile, turbidity and colour decreased from 44 NTU to 21 NTU and 70 TCU to 50 TCU, respectively. Low temperature affects alum coagulation performance, and generally requires more chemicals and additional flocculation time for promoting coagulation and flocculation processes. Mr. Jimmy Wavey, the Split Lake WTP operator, confirmed that alum alone did not work well in winter. A supplementary polymer had to be added to promote alum performance at low temperatures.

There is growing interest in the use of alternative coagulants to the traditional coagulant alum for water treatment at low temperatures. PACl is found to have many advantages over conventional alum in water treatment practice, especially at low temperatures. Many investigations were conducted on coagulants, however few studies have been carried out on coagulation flocs that may impact on coagulant performance. To address this issue, alum and PACl coagulation flocs were investigated at 19ºC and 5ºC in this research.

1.2 Objectives

The main objective of this research was to analyze the properties of alum and PACl coagulation flocs for evaluation of coagulant performances at 19ºC and 5ºC for the Split Lake WTP. In particular, the objectives were:

- To compare the settling properties of alum and PACl coagulation flocs
- To identify alum and PACl coagulation flocs sizes and their impacts on coagulant performances
- To investigate the impacts of temperature on alum and PACl coagulation flocs sizes

Chapter 2 Literature Review

The purpose of the literature review is to present an overview of the concept and principles of coagulation and flocculation processes. Certain important factors affecting coagulation and flocculation processes are discussed. As well, the method of microscopic particles analysis for coagulant performance evaluation is presented in this chapter.

2.1 Properties of natural organic matter and colloidal particles

The purpose of chemical coagulation and flocculation processes is to remove dissolved natural organic matter (NOM) and colloidal particles from water. The properties of NOM and colloidal particles are first reviewed in this section. This is fundamental in understanding coagulation reactions and mechanisms to be discussed in the next section.

2.1.1 Aquatic NOM

NOM is derived from decaying organic matter and dead organisms, and can impart colour, taste and odour to the water. In addition, NOM is a precursor of disinfection by-product when chlorine and other chemicals are used for disinfection and oxidation. For this reason, the removal of NOM from the drinking water stream is desired, and is becoming more important in the water treatment industry. Even when colour removal is not the main objective, NOM is required to be removed through coagulation by the U.S. Environmental Protection Agency (AWWA, 1999).

Humic substances are the major organic component of NOM in natural water. Many researchers agree that suspended solids, as well as turbidity-causing particles, have little effect on the removal of humic substances and colour (Dempsey et al., 1984; Miltner et al., 1994).

Turbidity mostly caused by clay particles, and colour mostly caused by NOM, are the target substances to be removed through coagulation and flocculation processes. Slight reductions in colour removal were detected at lower temperatures by some researchers; other researchers found that the temperature had no impact on the reduction of colour (Braul et al., 2001; Knocke et al., 1986; Randtke 1988; Hansen and Cleasby 1990).

No matter which view is taken, NOM or colour removal is not as sensitive to temperature as turbidity removal. Therefore, the efficiency of turbidity removal at high and low temperature was the focus of this study.

2.1.2 Colloidal particles

Surface water generally contains a wide variety of colloidal particles that may impart turbidity and colour to the water (Benefield et al., 1982). Inorganic particles include silts, clays, and mineral oxides. Organic particles include viruses, bacteria, protozoa and algae. Particle size is the most significant property responsible for the stability of colloidal dispersion in water. It may vary from a few tens of nanometers to a few hundred micrometers. Figure 2-1 shows the size range of waterborne particles. Generally, colloidal particles range in size from 0.001 to 10 µm. They are too small to be settled by gravity or filtrated through the common filtration media. In addition, colloidal suspension is quite stable in surface water due to its electrical surface charge.

Figure 2-1 Size spectrum of waterborne particles (Benefield, 1978)

Colloids can be classified as hydrophilic (water loving) and hydrophobic (water hating). Hydrophilic colloids, such as soap soluble starch and synthetic detergents, are readily dispersed in water. Their stability depends on their affinity for water molecules rather than on the slight charge they possess. Hydrophobic colloids, such as clay particles and metal oxide colloids, possess no affinity for water molecules, and owe their stability to the electrical charge they possess. The main organic and inorganic matter in surface water is hydrophobic.

The overall stability of a colloidal particle is controlled by double-layer repulsion forces and Van der Waals’s forces of attraction (Benefield et al., 1982). It is well known that most particles in water are negatively charged; they will adsorb positive ions from the water solution by electrostatic attraction. Thus, the diffuse double layer is formed as shown in Figure 2-2. Here, the Stern layer is referred to as the fixed zone of positive ions. The Zeta potential is the magnitude of the charge at the surface of shear, which can be a rough measurement for the stability of a colloidal particle. The repulsive force of the charged double layer disperses particles and prevents aggregation. As a result, particles with a high Zeta potential produce highly stable colloidal solution.

Forces that stabilize colloidal particles must be overcome and individual colloids must aggregate and grow bigger if they are to be separated from suspension. The process of destroying the stabilizing forces and causing aggregation of colloidal particles is called a chemical coagulation. Three essential steps, which are coagulant species formation, particle destabilization and physical interparticle collisions, will occur in the coagulation process. The first step, formation of active coagulant species, can be achieved through coagulant hydrolysis reactions by adding a chemical coagulant to water.

Figure 2-2 Electrical double layer of a negatively charged particle (AWWA, 1990)

2.2 Chemical coagulants properties

Coagulants are chemical reagents that can promote the coagulation process by destroying the stabilizing forces between colloidal particles and causing the aggregation of colloidal particles and NOM. Inorganic aluminium coagulants, which include aluminium salts and polymeric aluminium salts, are most commonly used in water and wastewater treatment. In this section the characteristics of two primary inorganic coagulants – alum and PACl – are reviewed.

2.2.1 Alum

When alum is added to water, it will dissolve and dissociate in water to produce trivalent Al^{3+} that can hydrate to form the aquoaluminum complex $Al(H_2O)_6^{3+}$ as shown in Figure 2-3 (Baes and Mesmer, 1976). Then, this complex $Al(H_2O)_6^{3+}$ can have a series of hydrolytic reactions in which H_2O molecules in the hydration shell are replaced by OH^- ions. Thus, a variety of soluble aluminium species is formed and dispersed into the bulk flow by rapid mixing. Researchers have demonstrated that the predominant Al species of alum is the mononuclear aluminium hydroxide species, such as $Al\ (H_2O)_6^{3+}$, $Al(OH)^{2+}$ and $Al(OH)_4^-$ in equilibrium with an amorphous aluminium hydroxide precipitate (Van and Edzwald, 1990). The maximum size of 280 Å aluminium hydroxide species was assumed by Dentel (1988) in the modelling of the alum coagulation process.

Figure 2-3 Structure of aquoaluminum ion and monomeric hydrolysis products (Baes and Mesmer, 1976)

2.2.2 PACl

PACl is a relatively new polymeric aluminium coagulant increasingly being used in water treatment. It is produced under controlled conditions by the partial neutralization of aluminium salts. Researchers have demonstrated that the predominant aluminium species of PACl are in polymeric forms with the formula of $Al_{13}O_4(OH)_{24}(H_2O)_{12}^{7+}$

(abbreviated as Al_{13}^{7+}), in equilibrium with a different amorphous phase $Al(OH)_3$ (Parthasarathy and Buffle, 1985; Bertsch et al., 1986; Bertsch, 1987; Van Benschoten and Edzwald, 1990; Parker and Bertsch, 1992). The proposed structure of Al_{13}^{7+} polymer is composed of a tetrahedrally coordinated Al atom located at the centre of a cage surrounded by 12 octahedrally coordinated Al atoms (Johansson,1960).

The molecular weight of polymeric species is higher than that of monomeric species. This is supported by technical data provided by the Summit Research Labs, shown in Table 2-1. However, there is few research studies on the size of polymeric species. Parthasarathy and Buffle (1985) conducted a study of polymeric aluminium hydroxide solution and found that the size of Al_{13}^{7+} polymeric aluminium hydroxide species was between 10-20 Å. Other researchers used small-angle x-ray scattering and found that the size of the Al_{13}^{7+} species was 25 Å (Bottero et al., 1982). Compared with monomeric hydrolysis species, it seems that the size of polymeric species is smaller than that of monomeric species. If this is the case, the density of polymeric species would be higher than that of monomeric species.

Table 2-1 Molecular weight of monomeric and polymeric species (Summit Research Labs)

Hydrolysis species	Complex Formula	Molecular weight (Approximate)
Al^{3+}	$Al(H_2O)_6^{3+}$	<150
$Al(OH)_3(s)$	$Al(OH)_3(H_2O)3$	<150
$Al_6(OH)_6^{6+}$	$Al_6(OH)_{12}(H_2O)_{12}^{6+}$	600
$Al_{13}O_4(OH)_{24}^{7+}$	$Al_{13}O_4(OH)_{24}(H_2O)_{12}^{7+}$	1,000
$Al_{54}(OH)_{144}^{18+}$	$Al_{54}(OH)_{144}(H_2O)_{38}^{18+}$	4,500

Some researchers (Matsui et al., 1998, Rak et al., 2001, O'Melia et al., 1989) conducted an investigation of chemical dynamic analysis on alum and PACl coagulation. They found that PACl destabilized particles faster and reduced more particles than alum.

2.2.3 Solubility

As mentioned previously, metal Al^{3+} ion exists in aqueous solutions as hydrated ion [$Al(H_2O)_6{}^{3+}$], and causes some complex hydrolysis reactions to occur between the hydrated metal ion and hydroxyl ions. Such reactions would lead to the formation of monomeric or polymeric species. The process of such hydrolysis reactions and thermodynamic conditions for these species is summarized in Table 2-2. These reactions are quick and are reversible in water solution.

Table 2-2 Aluminium hydrolysis reactions (Pernistsky and Edzwald, 2003)

Chemical equation	Equilibrium expression	pK	
		20˚C	5˚C
$Al^{3+} + H_2O = Al(OH)^{2+} + H^+$	$K_{11}=[Al(OH)^{2+}][H^+]/[Al^{3+}]$	5.12	5.65
$Al^{3+} + 2H_2O = Al(OH)_2{}^+ + 2H^+$	$K_{12}=[Al(OH)_2{}^+][H^+]^2/[Al^{3+}]$	10.45	11.56
$Al^{3+} + 4H_2O = Al(OH)_4{}^- + 4H^+$	$K_{14}=[Al(OH)_4{}^-][H^+]^4/[Al^{3+}]$	23.57	25.33
$Al(OH)_3(s) = Al^{3+} + 3OH^-$	$K_{sp}=[Al^{3+}][OH^-]^3$	31.67	32.40
$Al^{3+} + 28H_2O = Al_{13}O_4(OH)_{24}{}^{7+}+32H^+$	$K=[Al_{13}O_4(OH)_{24}{}^{7+}][H^+]^{32}/[Al^{3+}]^{13}$	102.20	113.4

The reactions presented above show that hydrogen ions are liberated when metal hydroxocomplexes are formed. Based on these chemical reactions, the equations can be developed as follows:

$Al(OH)_3(s) = Al^{3+} + 3OH^- \quad K_{sp} = [Al^{3+}][OH^-]^3$

$\log K_{sp} = \log [Al^{3+}] + 3 \log [OH^-] = \log [Al^{3+}] + 3(pH - 14) = -31.67$

$\log [Al^{3+}] = 10.33 - 3pH \quad \cdots\cdots \quad (1)$

$Al^{3+} + 4H_2O = Al(OH)_4^- + 4H^+ \quad K_{14} = [Al(OH)_4^-][H^+]^4/[Al^{3+}]$

$\log K_{14} = \log [Al(OH)_4^-] + 4 \log [H^+] - \log [Al^{3+}] = -23.57$

Use equation (1) to substitute for $\log [Al^{3+}]$, then we can get:

$\log [Al(OH)_4^-] = pH - 13.91 \quad \cdots\cdots \quad (2)$

Similar way for: $Al^{3+} + H_2O = Al(OH)^{2+} + H^+ \quad K_{11} = [Al(OH)^{2+}][H^+]/[Al^{3+}]$

$\log [Al(OH)^{2+}] = 5.21 - 2pH \quad \cdots\cdots \quad (3)$

Based on the above equations (1), (2) and (3), a log [species] vs. pH diagram can be plotted for the $Al(OH)_{3(am)} – H_2O$ system. Such diagrams, as shown in Figures 2-4 and 2-5, will demonstrate the variation in salt solubility with pH and the minimum salt solubility (Benefield, 1982).

As shown in Table 2-2, the equilibrium constants for all aluminium hydrolysis reactions change with temperature. And this will have an effect on the formation of Al species. Pernitsky and Edzwald (2003) conducted the solubility tests for alum and PACl at 5ºC and 20ºC. They found that the solubility of $Al(OH)_{3(am)}$ for alum and PACl were significantly different. PACl has a higher solubility and a higher pH of minimum solubility than alum.

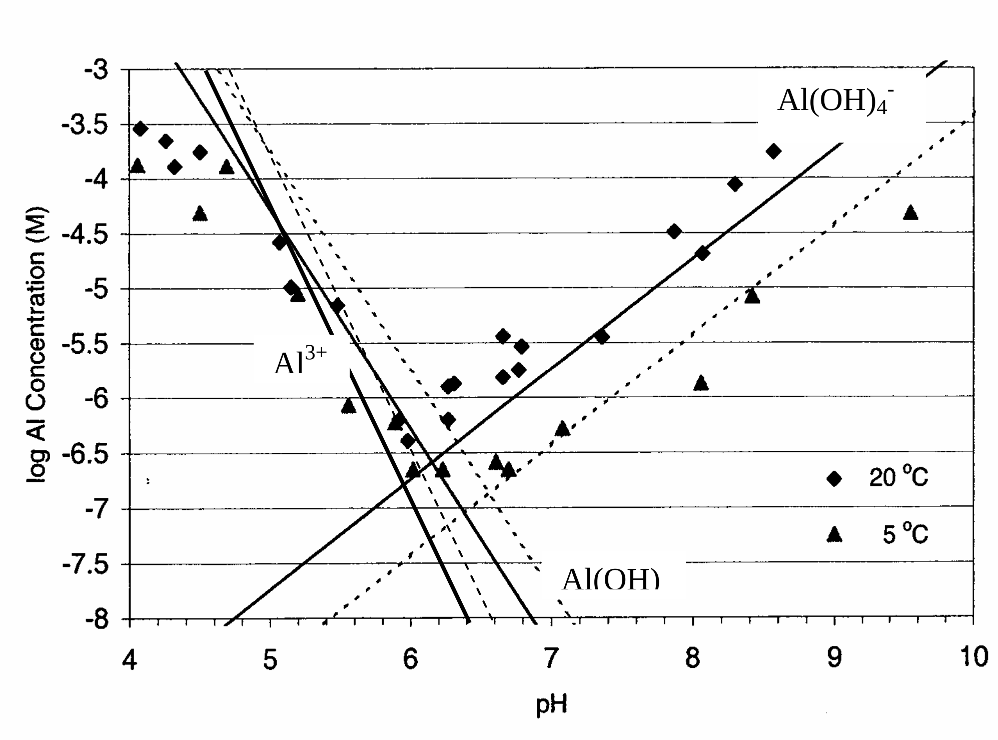

Fig. 2-4 Effects of temperature on alum solubility (Pernistsky, 2001)

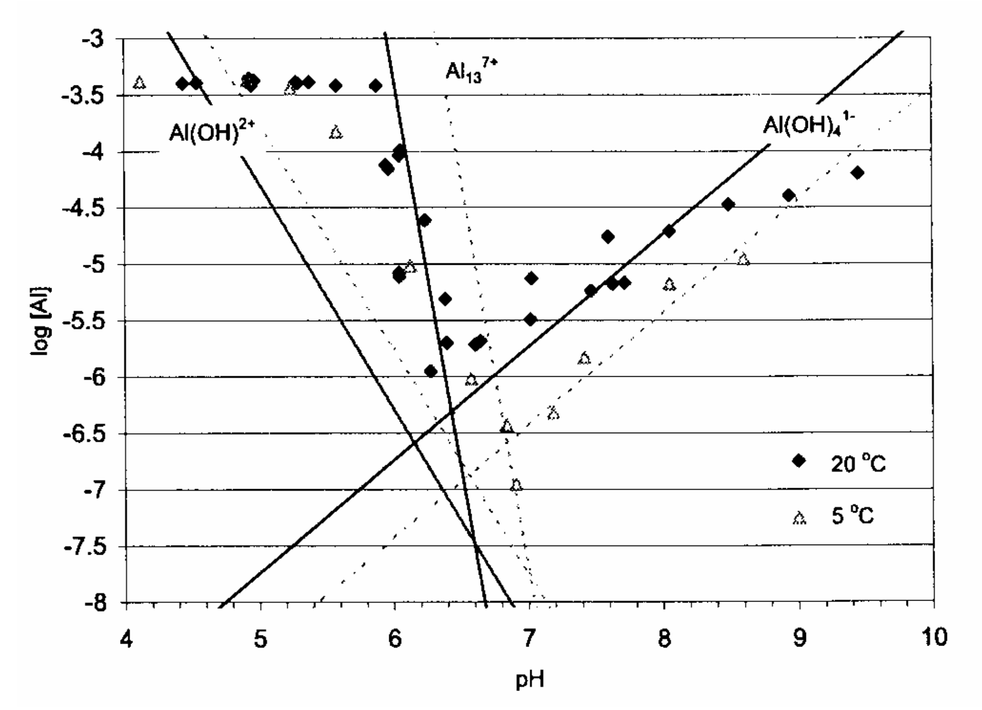

Fig. 2-5 Effects of temperature on PACl solubility (Pernistsky, 2001)

Figures 2-4 and 2-5 present the effects of temperature on the solubility of alum and PACl. The solid and dashed lines, shown in Figures 2-4 and 2-5, are theoretical solubility in equilibrium with $Al(OH)_{3(am)}$ in aqueous solution at 20ºC and 5ºC, respectively. As well, the minimum solubility values of alum and PACl are presented in Table 2-3.

Table 2-3 Alum and PACl minimum solubility (Pernistsky and Edzwald, 2003)

Coagulant	20ºC		5ºC	
	pH	Solubility (mm/l Al)	pH	Solubility (mm/l Al)
Alum	6.0	16	6.2	3
PACl	6.3	29	6.5	4

Figure 2-4 illustrates that monomeric species rather than polymeric species are formed in alum aqueous solution. Figure 2-5 illustrates that some monomeric species as well as high charge and high molecular weight polymeric species are formed in PACl aqueous solution. As well, Table 2-3 indicates that both alum and PACl solubility decreased as temperature decreased, and the solubility of PACl is always higher than that of alum.

2.3 Coagulation and Flocculation processes in water treatment

Once the initial coagulant hydrolysis reactions are completed, the active monomeric and polymeric species described above will react with those contaminants, such as colloidal particles and dissolved NOM during coagulation and flocculation processes.

2.3.1 Coagulation process

Chemical coagulation is a complex process that can combine colloidal particles and dissolved NOM into large aggregates. It is a key component of accepted water treatment practice in which coagulation/flocculation, sedimentation, filtration and disinfection processes are combined to clean the water by removal of colloidal particles, NOM, and some microbiological contaminants.

2.3.1.1 Coagulation mechanisms

During coagulation and flocculation processes, the aggregation of colloidal particles and NOM can be achieved by four primary mechanisms (Amirtharajah and Mills, 1982; Dempsey et al., 1985; Hundt and O'Melia 1988; Randtke 1988; Edzwald and Van Benschoten, 1990):

- Adsorption and Charge neutralization/Destabilization (colloids only)
- Enmeshment in precipitated floc particles (colloids only)
- Adsorption onto precipitated floc particles (NOM only)
- Complexation / Precipitation (NOM only)

Here it should be noted that a combination of these mechanisms may occur during coagulation and flocculation processes.

Charge neutralization is referred to as the direct interaction of a charged Al(III) hydrolysis product such as $Al(OH)^{2+}$ or Al_{13}^{7+} with a negative charged colloid. As mentioned above, when alum or PACl is added to water, active monomeric or polymeric species are formed. These chemical species carrying a positive charge are capable of being adsorbed on the surface of colloidal particles. Thus, colloidal particles are destabilized.

Enmeshment (or sweep-floc coagulation) is referred to as the physical mechanism where colloidal particles are entrapped in the aluminum hydroxide precipitate formed at neutral or basic pH. When alum or PACl is added to water in sufficient amounts, rapid formation of aluminum hydroxide precipitate will occur. Colloidal particles can be enmeshed in these precipitates as well as colliding with them afterward. Compared with other mechanisms, the enmeshment mechanism is relatively slower and generally gives better clarification (Letterman et al., 1973).

Complexation/Precipitation is referred to as the chemical reaction of positively charged metal hydrolysis species with the negative organic molecule (Edzwald and Van Benschoten, 1990). These chemical reactions between Al and organic ligands are quite complex and are not well known. However, the products of these reactions can be thought of as, either a soluble metal-organic complex Al-NOM, an insoluble metal-organic precipitate $\text{Al-NOM}_{(am)}$, or a combination of those two products (Browne and Driscoll, 1993).

Adsorption NOM is capable of being adsorbed by metal hydroxide precipitates formed through coagulant hydrolysis reactions. This mechanism is quite different from the complexation/precipitation mechanism discussed above, where NOM adsorbs onto the surface of precipitate, rather than forming a precipitate itself.

2.3.1.2 Rapid-mixing

Rapid-mixing is required in the coagulation process for complete mixing of the coagulant and raw water. Particle destabilization and early-stage flocs formation occur during this rapid-mixing. Typical rapid-mixing methods in water treatment plants include:

- Backmix mechanical mixing
- In-line mixer
- Hydraulic jump
- Compressed air
- Pump mixing
- Grid mixing

Mechanical mixed units were widely used in the past. However, they don't provide uniform mixing, and this is harmful to the adsorption mechanism. In recent decades, these units have been replaced by static mixers, which are more efficient for coagulant rapid-mixing in line (Benefield et al., 1982).

Another concern in a rapid-mixing system is total detention time or duration of the mixing. Proper design of a rapid-mixing unit can optimize the coagulation process, result in reduced coagulant demands, and improve aggregation in the flocculation unit. In water treatment practice, a velocity gradient G from 500 to 1000 s^{-1} and a detention time from 10 to 60 seconds are commonly used for a rapid-mixing system design.

2.3.2 Flocculation process

The physical process of prompting interparticle contacts is referred to flocculation. Slow-mixing is required in the flocculation units for the aggregation of destabilized particles. Proper design of flocculation units can, not only improve coagulation process, but also promote flocs removal in subsequent separation processes such as sedimentation, flotation, or filtration. Same as that rapid-mixing system, mixing intensity and detention time are two important parameters for flocculation units. The mixing intensity is measured by the mean velocity gradient G which is related to the amount of mixing power P as presented as equation 1 (Camp, 1955). Velocity gradients G in flocculation units should be high enough to promote particles contacts for aggregation. The higher the velocity gradient G, the more intense the mixing is.

$$G = (P/\mu V)^{0.5} \quad \text{.........................} (4)$$

Where: G = mean velocity gradient (s^{-1})

P = power into mixing chamber (w)

μ = absolute viscosity of the water (Pa-sec)

V = volume of basin (m^3)

As well, detention time should be long enough for the particles to be exposed to the velocity gradient in the flocculation units. In water treatment practice, typically the velocity gradient from 15 to 80 s^{-1} and the detention time from 10 to 60 minutes are normal ranges for flocculation design (AWWA Manual M37, 1992).

Collisions between destabilized particles in flocculation units are achieved by three separate mechanisms (Weber, 1972):

(1) Brownian diffusion or perikinetic flocculation due to the continuous bombardment by surrounding water molecules;

(2) Fluid shear or orthokinetic flocculation due to velocity differences or gradients in either laminar or turbulent fluid fields;

(3) Differential sedimentation due to gravities of particles, as faster settling particles overtake and collide with slower settling particles.

The collision frequencies N_{ij} between particles of size d_i and n_j with concentration of n_i and n_j can be expressed by the following equation (AWWA, 1990):

$$N_{ij} = k(i,j)\, n_i\, n_j \quad \text{......} \quad (5)$$

Where k(i,j) is a collision frequency function that is related to the flocculation mechanism and particle size. The equation of collision frequencies for the above three flocculation mechanisms can be expressed as follows:

For Brownian diffusion (perikinetic flocculation)

$$(\mathrm{Nij})_{pe} = \frac{2}{3}\frac{kT}{\mu}\frac{\left(d_i + d_j\right)^2}{d_i d_j} n_i n_j \quad \text{......} \quad (6)$$

For laminar shear (orthokinetic flocculation)

$$(\mathrm{Nij})_{or} = \frac{1}{6} n_i n_j \left(d_i + d_j\right)^3 G \quad \text{......} \quad (7)$$

For differential sedimentation

$$(\mathrm{Nij})_{se} = \frac{\pi g(S-1)}{72\mu}\left(d_i + d_j\right)^3\left(d_i - d_j\right) n_i n_j \quad \text{......} \quad (8)$$

where: k = Boltzmann’s constant

T = absolute temperature

μ = fluid absolute viscosity

d = particle diameter

G = mean velocity gradient

g = gravitational constant

The transport mechanisms in flocculation are related to the size of particles present in suspension. Perikinetic flocculation predominates when particles are less than 0.1 µm. Once these small particles aggregate to a size of approximately 1 µm, orthokinetic flocculation will predominate and promote further aggregation by stirring and settling (Benefield et al., 1982). The range of flocculated floc size is from 1 to 100 µm. Most large size and dense flocculated flocs are settled and removed in the settling tank. Suspended particles of 10 µm or larger can be removed through a granular media filter.

2.3.3 Coagulation Jar Tests

The quality of surface water changes with season and weather. As a result, the coagulant dosages have to be adjusted to allow for variations in water turbidity and NOM. An underdose of coagulant may cause the sample to appear cloudy with no floc and settling phenomena. An overdose of coagulant may form dense floc that may be fragile and fluffy. It would not settle well when the stirrer is turned off. Suitable dosages of coagulant would produce a good floc, which is heavy and tight, and would settle well once the stirrer is turned off. However, coagulant dosages can not be calculated, they have to be determined experimentally by jar test.

The jar test is a simple effective method that simulates the coagulation/flocculation process of the existing or proposed water treatment plant. It is a widely used laboratory test for coagulation and flocculation control in water treatment plant operations and design.

A bench-scale jar tester consisting of a series of standard beakers and a mixing device with standard mixer paddles is presented in Figure 2-6. The purpose of a jar test is coagulant type and dosage selection, coagulant aid and dosage selection, determination of optimal pH, determination of the point of chemical addition, optimization of mixing time and intensity for rapid and slow mixings (Amirtharajah and O'Melia, 1990).

Figure 2-6 Schematic of Jar tester

The circular glass 1-L or 2-L beakers are conventional jars used in the past. However, these circular containers may not have been a good choice since the solution rotates rather than mixes turbulently, and the rotation of the treated water does not stop quickly when the slow mixing ends (Koether et al., 1993). The square plexiglass 2-L beakers, as shown in Figure 2-6, have recently been used as an alternative to the circular glass beakers.

Compared with the conventional circular jars, the square plexiglass jars have the following advantages: (1) the square configuration reduces the rotation of the treated water during mixing, (2) the thick wall and low heat conductivity of the square plexiglass beaker reduce the change in water temperature during the jar test, and (3) the treated water samples are more quickly and easily taken from the sampling tap. Mhaisalkar et al. (1986) demonstrated that square jars provide the greatest velocity gradient at a given impeller speed.

2.4 Type of coagulant and coagulant dosage

There are many chemicals, such as alum, aluminium chlorohydrate, sodium aluminate, PACl, ferric chloride, ferric sulphate, ferric chlorosulfate, PACl cationic polymers and polyiron chloride, used as primary coagulants in water treatment plants. Among these coagulants, alum has been widely used as a primary coagulant in water treatment for many decades. However, alum performs poorly in cold water and requires coagulant aids. PACl, a relatively new polyaluminum coagulant, has gradually been replacing alum in water and wastewater treatment.

Coagulant dosage required is highly related to the source water characteristics, as well as the type of coagulant used. As mentioned previously, the optimum coagulant dosage can not be calculated. Rather, it has to be determined experimentally by minimizing turbidity or the remaining total particle count (Lai et al., 1975; Yeh et al., 1981; Reed et al., 1986). However, due to the differences in the hydrodynamics of the two systems, the optimal dosage determined by the bench-scale jar test is usually lower than that in a full-scale plant. Therefore, the experimental results can not be transferred directly into plant design or operation appraisal, and may have to be adjusted.

2.5 Factors affecting coagulation and flocculation processes

Many factors may influence the coagulation/flocculation process. Not all will be discussed here. Only important factors such as raw water quality, type of coagulant, coagulant dosage and mixing conditions will be individually discussed in this section.

2.5.1 Raw water quality

2.5.1.1 Turbidity

Turbidity is caused by suspended colloidal clay particles, such as silt, clay, microscopic organisms, soluble colored organic compounds, finely divided organic or inorganic matter (Benefield et al., 1982). Higher turbidity water containing higher amount of particles generally requires higher dosages of coagulant.

Turbidity is defined as the amount of light scattered by particles in water solution (AWWA, 1990). It is one of the most commonly used parameters for evaluation of coagulation and flocculation processes, as well as an indicator of drinking water quality. As the number of particles increase, a higher intensity of light is scattered and a higher turbidity value is obtained. The process of light scattering by particles is quite complex. The angular distribution of scattered light is related to such conditions as particle size, shape, composition and the wave length of the incident light (Sethi et al., 1996). Although the measurement of turbidity is quite simple and easy to operate, it has limitations. For example, turbidity is a crude and indirect measurement and is not sensitive to small particles such as Giardia and Cryptosporidium pathogenic microorganisms (LeChevallier and Norton, 1992). However, this problem can partially be overcome by the technology of particle counting discussed later in this section.

Turbidity is measured by turbidimeter and is expressed as a nephelometric turbidity unit (NTU). The Canadian Drinking Water Quality Guidelines requires less than 1 NTU for filtered water.

2.5.1.2 Colour

Colour is caused by colloidal forms of iron and manganese or more commonly by NOM (Benefield, 1982). Higher coloured water containing higher amounts of NOM generally requires higher dosages of coagulant.

Colour is generally measured by visual comparison of the sample with known concentrations of coloured solution, and is expressed as true colour unit (TCU). The Canadian Drinking Water Quality Guidelines requires less than 15 TCU for filtered water.

2.5.1.3 pH/Alkalinity

pH is defined as the negative log of the hydrogen ion concentration. It is one of the important raw water quality parameters for coagulant selection. During the coagulation process, the pH of the water affects the chemistry of the coagulant, such as solubility and speciation, as well as the charge on the particles and NOM. pH is controlled by the equilibrium achieved by dissolved coagulants in water. Generally speaking, the coagulation process performs better if the practical pH is close to the pH of minimum solubility of the coagulant.

Alkalinity is a measure of water's capacity to neutralize acids and is expressed in terms of $CaCO_3$. It is related to pH. Higher alkalinity water has higher pH. Since metal coagulants are acidic, coagulant addition consumes alkalinity. High alkalinity water may need more coagulant addition to decrease the pH to a favourable value for effective coagulation (Tseng et al., 2000). Higher alkalinity consumption is observed after addition of alum than PACl (Pernitsky and Edzwald, 2003).

2.5.1.4 Temperature

Water temperature is another important raw water quality parameter for coagulant and dosage selection. It is well known that the surface water temperature changes gradually with seasons. This results in the effects on water treatment processes, such as the type of coagulant and the rate at which chemicals dissolve and react. As mentioned previously, cold water decreases the solubility of alum and PACl coagulants, increases water viscosity, and retards the kinetics of hydrolysis reactions and particle flocculation. Thus, higher coagulant dosages and additional flocculation time are required at low temperature (Frank et al., 2000). Low water temperatures decrease the rates of coagulant dissolution, precipitation, cell enmeshment and floc formation, especially when alum was used (O’Connor, 2001). Warm water often causes an increased level of algae and other organic matter in raw water.

Temperature also significantly affects turbidity and particle counts during coagulation (Braul et al., 2001). However, dissolved organic carbon (DOC) and colour removal are not sensitive to temperature (Knocke et al.,1986; Randtke, 1998; Hanson and Cleasby, 1990).

2.6 Particle size and distribution analysis

2.6.1 Particle size and distribution application in water treatment

As mentioned previously, the removal of particles from water is the main purpose of water treatment. There are many methods that have been used as particle removal performance indicators, such as:

- Turbidity measurement
- Filterability number
- Conductivity
- Particle counting

Among these methods, turbidity and particle counting are two major performance measures of particle removal in water treatment processes. In recent decades, the application of particle counting has attracted the attention of both researchers and professionals since it can provide more information about the nature of the particles.

Physical properties of particles, such as size, shape, density, porosity, surface charge, and settling velocity, may influence their behaviour in water and have some relationship to water treatment efficiency. As previously mentioned, particle size is the most significant property responsible for the stability of colloidal dispersion in water. Due to the increasing demand for a higher level of water treatment, it is also required to know more about the nature of particles and their behaviour in water during treatment processes. Particle size analysis is usually applied in drinking water treatment for monitoring and controlling filtration process performance. Analysis of sizes of flocs formed in the coagulation and flocculation processes are not routinely conducted.

Particle size distribution (PSD) analysis can produce direct information about particulate material in water. Through measuring and analyzing the amount of different-sized particles in the raw water as well as in the effluent of each unit, we can evaluate water treatment process efficiency, assess operational problems, and design treatment processes in water and wastewater engineering.

2.6.2 Microscopic particles measurement and analysis

There are four methods that are commonly used for particles analysis. Such as:

- Electrical resistance
- Light-blocking
- Laser light-scattering
- Microscopic examination

The electrical resistance method is based on the conductivity of the fluid. It is not widely used due to the complex process. The sample has to be mixed with a strong electrolyte to increase specific conductance of the solution (Tate et al., 1977). Although light-blocking and light-scattering methods are widely used in water treatment application, they have limitations and can not detect transparent particles or those smaller than about 1µm and (Gorczyca and London, 2003). However, this problem can be overcome by the microscopic method. Through a microscopic technique, the properties of particles such as area, length, number, density, shape, and type can be caught, and particle size range can be broader.

Chapter 3 Experimental Methods and Results

3.1 Preliminary work

3.1.1 Raw water quality

A 20-L tank of raw water sample collected from the intake of the Split Lake was delivered to the Environmental Engineering Laboratory at the University of Manitoba on April 9, 2002. Initially, turbidity, colour, pH and temperature of the raw water were measured. After 12 days, identical measurements for the settled water were conducted. The results are presented in Table 3-1.

Table 3-1 Split Lake raw water quality (April 2002)

Sample	**Temperature (°C)**	**pH**	**Colour (TCU)**	**Turbidity (NTU)**	
				Original sample	**Centrifuged sample**
Initial	19	7.4	50	21	3
Settled after 12 days	22	7.4	40	12	3

Table 3-1 shows that the turbidity of centrifuged samples did not change after 12 days. This result indicated that the turbidity of the raw water at Split Lake is quite stable.

In addition, raw water particles were collected and sealed on slides for microscopic analysis. The process of slide sample preparation is presented in section 3.3.1. The microscopic analysis is discussed in the next chapter.

3.1.2 Preliminary coagulation jar tests

The jar test procedure for optimizing the dosage of coagulant includes the following steps:

(1) While rapidly mixing the raw water, six different dosages of coagulants are added to each jar containing the same-source raw water.

(2) The coagulants are rapidly mixed for 30 to 60 seconds at the maximum possible mixing intensity.

(3) The stirring speed is reduced while slowly mixing the suspensions at 25 to 40 rpm for 15 to 30 minutes.

(4) The stirring apparatus is stopped to allow the floc to settle for 30 to 45 minutes.

(5) Water samples are taken from the sampling tap at a fixed distance below the surface of the water in the jars.

(6) The turbidity of the water samples is measured.

In addition to residual turbidity in jar tests, other parameters such as colour, zeta potential, streaming current, settling velocity and particle size analysis may be used as performance indicators for coagulation control. In this study, analysis of residual turbidity and flocs size was conducted to evaluate coagulation performance at the Split Lake water treatment plant.

The coagulants and coagulant aids used in this research were prepared and supplied by Vopak Canada Limited. The physical properties of these chemicals are summarized in Table 3-2.

Table 3-2 Coagulant physical properties

Coagulant	**Symbol**	**Strength (% wt as Al_2O_3)**	**Specific Gravity**	**Basicity (% wt)**
Aluminum sulfate	Alum	8.3	1.33	0.2
SternPAC (polyaluminum chloride)	PACl	10.2	1.2	50
Sumalchlor 780 (aluminum based product)	SC780	17.8	1.3	75
Sumaclear 50 (aluminum based product)	SC50	23.5	1.34	84
PASS 100 (polyaluminum sulfate)	PASS100	9.81	1.32	54
AluFer C & S (aluminum & iron combinations)	ACS	5.8	1.35	N/A
Ferric chloride	$FeCl_3$	11 (% iron)	1.32	2

The Phipps and Bird PB-700 ^{TM} Jar Tester combined with six 2-L square beakers, shown in Appendix D, were employed in this experiment. Prior to the coagulation jar tests, 10 mg/ml $Al_2(SO_4)_3 14H_2O$ alum solution and 0.1 mg/ml Superfloc C-591 polymer solution were prepared. As well, synthetic water was prepared for the preliminary jar tests.

3.1.2.1 Synthetic water preparation

Split Lake is approximately 500 miles away from Winnipeg. It is difficult and costly to transfer large amounts of water from there to Winnipeg. Therefore, the synthetic water having the same turbidity and colour as Split Lake water was prepared in the laboratory for an alternative coagulant selection.

In order to simulate the colour of raw water, wood chip water was made prior to the synthetic water preparation. This was achieved by taking a clean 2-L flask, adding approximately 100 g of wood chips to the flask, and filling it to the 2000 ml mark with distilled water. Then it was boiled on an electric heater until most of the wood chips settled down. The flask was cooled to the room temperature. Thus, the wood chip water was obtained by decanting the top water from the flask.

About 80-L synthetic water was made by mixing clay, wood chip water and lime with tap water based on the raw water quality. The synthetic water was poured into two 40-L clean containers. One container of the water was used for the jar tests at room temperature. The other one, stored in a refrigerator, was used for the jar tests at 5ºC.

3.1.2.2 Alternative coagulant selection

In order to choose an alternative coagulant to alum for the Split Lake WTP, a series of bench-scale jar tests was initially conducted using synthetic water to determine the effectiveness of primary coagulants including alum, $FeCl_3$, PACl, SC780, SC50, PASS100 and ACS under the condition of 30 seconds of 100rpm flash mixing followed by 15 minutes of flocculation at 40 rpm, and 30 minutes of settling. The coagulated water was analyzed for colour, turbidity, pH and alkalinity. Thus, one alternative coagulant could be chosen based on the treated water quality.

Similar bench-scale jar tests were conducted with synthetic water for the optimum dosages of Superfloc C-591 polymer and Powdered Activated Carbon (PAC) selection as well as for the optimum flocculation time selection for both alum and the alternative coagulant. The results of above jar tests are all presented in Appendix A.

The characteristics of the synthetic water, based on the quality of the raw water, are shown in Figure 3-1.

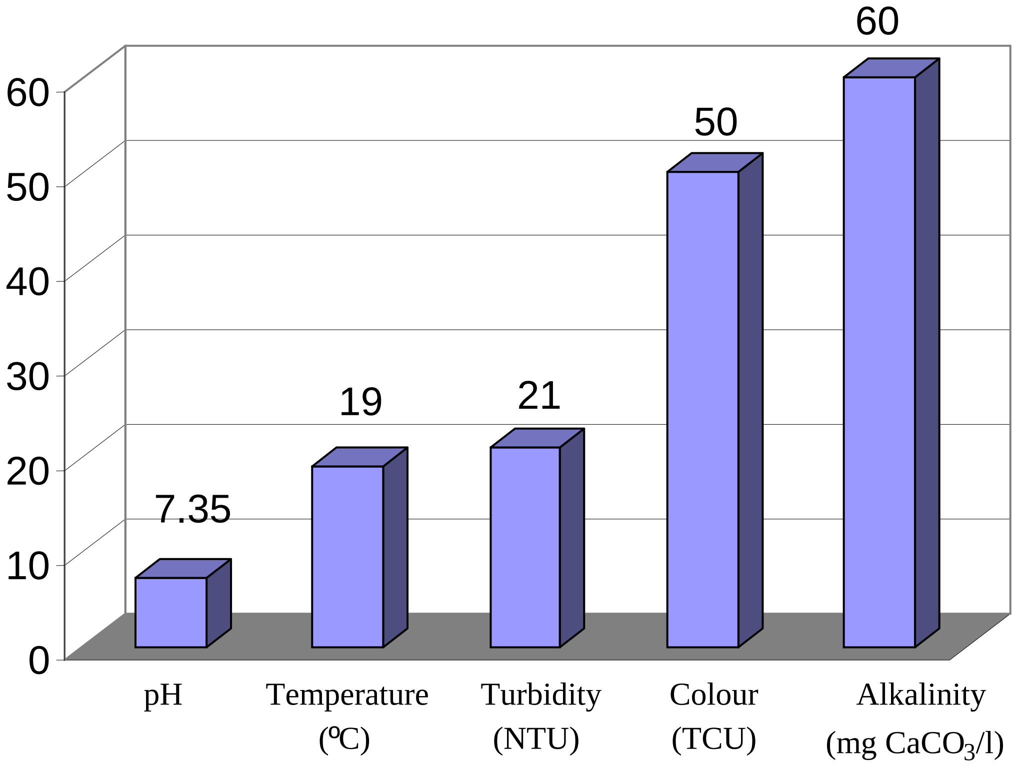

Figure 3-1 The synthetic water parameters

As mentioned previously, turbidity and true colour are two important indices for water quality. The less the turbidity and true colour, the better the water quality is. For the purpose of discussion and analysis, the graphs of the effect of each coagulant on turbidity and colour removal are plotted in Figures 3-2 and 3-3.

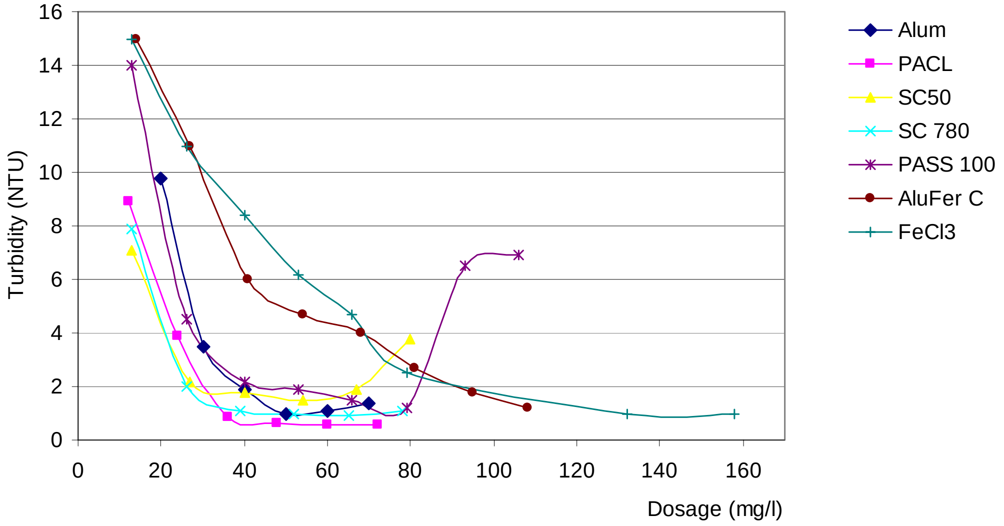

Figure 3-2 Effects of each coagulant on turbidity removal

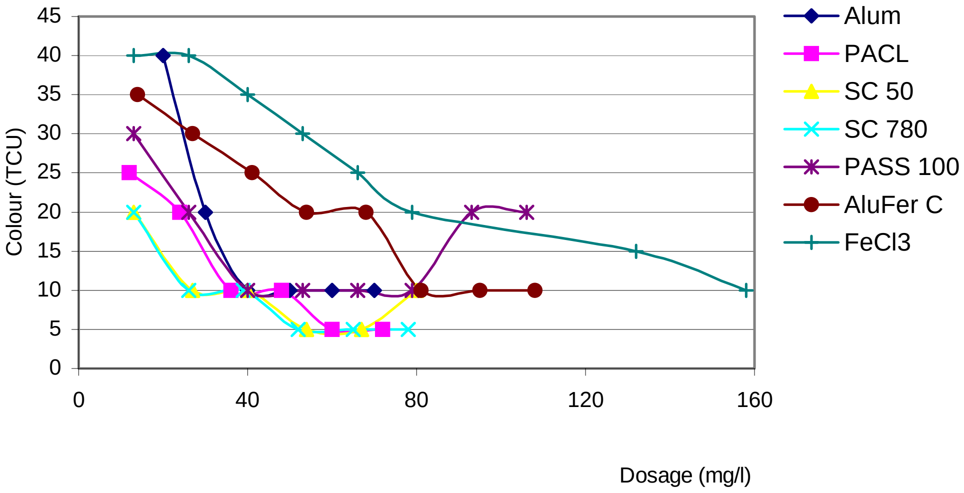

Figure 3-3 Effects of each coagulant on colour removal

From Figures 3-2 and 3-3, we can see the differences in the effect of each coagulant on turbidity and colour removal. Low dosage of 36 mg/l PACl caused turbidity and colour decrease to 0.88 NTU and 10 TCU, respectively. This result indicated that PACl is more effective than other coagulants in removing turbidity and colour from the raw water. Thus, PACl was initially chosen as an alternative coagulant.

The combined effects of alum and PACl with polymer and PAC on turbidity and colour removal were different. This can be seen in Appendix A Tables A-10 and A-11. When 3 mg/l PAC was used, the optimum dosages of polymer were 1 and 0.5 mg/l for alum and PACl, respectively.

In addition, it was found that the optimum flocculation time of alum and PACl was 30 and 15 minutes, respectively. This result, presented in Appendix A Table A-12, indicates that PACl destabilized particles faster than alum.

3.2 Alum and PACl coagulation jar tests

3.2.1 Coagulation jar tests at the Split Lake WTP

In order to gain further insight into the water quality and WTP coagulation and flocculation conditions, a field investigation at the Split Lake WTP was taken from July 29 to August 1, 2002. A series of bench-scale coagulation jar tests was conducted on site using raw water. Alum and PACl, as well as polymer and PAC, were used in the jar tests.

The raw water, taken from the intake of the Split Lake WTP, was initially analyzed on site. The results are presented in Figure 3-4. Compared with the water quality tested in April 2002, turbidity increased from 21 to 44 NTU, and colour increased from 50 to 70 TCU. As a result, the optimum dosages of PACl selected using the synthetic water had to be adjusted. The bench-scale jar tests were conducted to identify PACl and polymer with the Split Lake raw water.

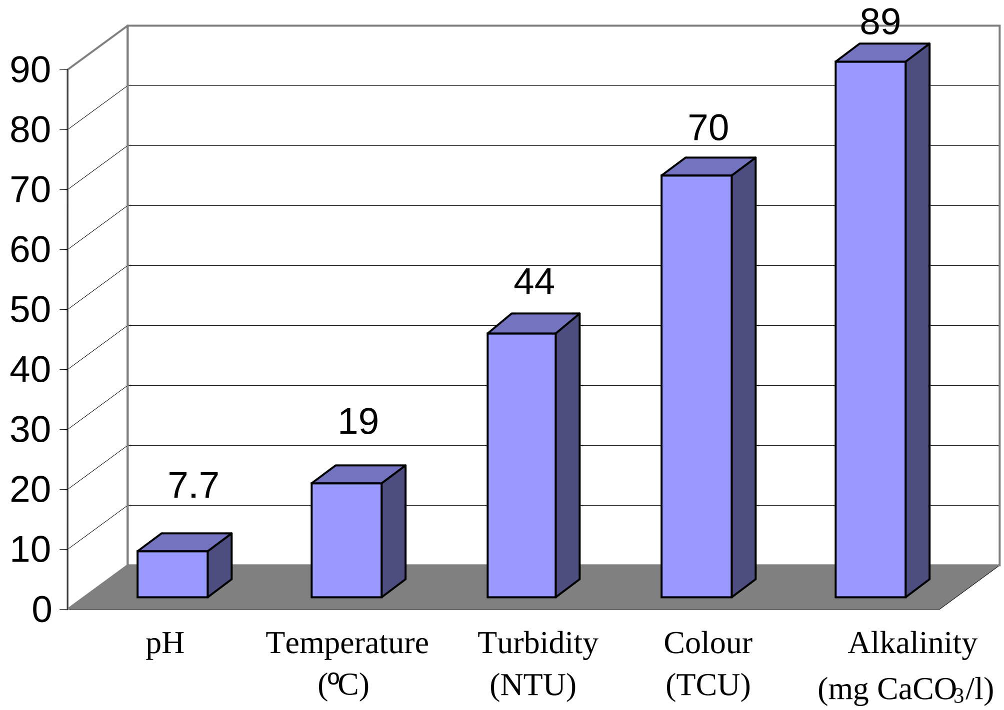

Figure 3-4 Split Lake raw water quality (Aug. 2002)

The Split Lake WTP infrastructure is quite simple; all chemicals such as power alum, polymer, PAC and chlorine are fed manually. There are no on-line monitoring and recording facilities for water turbidity and chlorine residuals in the WTP. Mr. Jimmy

Wavey, the treatment plant operator, indicated that the quality of raw water changes with the seasons. The dosages of alum and polymer have to be adjusted with the seasonal variability in turbidity. Based on the raw water quality and operation record of the plant, alum was tested at dosages of 60, 73, 80, 90, 100, 110 mg/l; PACl was tested at dosages of 48, 60, 72, 84, 108 mg/l; and polymer was tested at dosages of 0.4, 0.5 and 0.6 mg/l. The tests results, presented in Appendix B, are later analyzed and discussed in this section.

It was expected that pH and alkalinity of the raw water, presented in Appendix B Tables B-1 and B-2, decreased after alum or PACl addition to the raw water samples. The addition of alum or PACl caused a series of hydrolysis reactions to occur. Hydrogen ions were produced, hence the pH of raw water was reduced, and the alkalinity was reduced as well.

When alum or PACl was added to the raw water, many flocs were formed during the rapid and slow mixing, and then settled to the bottom during the settling time. This phenomenon indicated that both alum and PACl promoted the coagulation process and caused the aggregation of colloidal particles and dissolved NOM. However, the effectiveness of alum and PACl in the coagulation process was not the same. The results, presented in Appendix B Tables B-1 and B-2, indicated that PACl was more effective than alum in the colour and turbidity removal from the raw water. The optimum dosage of PACl was 84 mg/l, lower than the alum optimum dosage of 100 mg/l. The optimum dosage of polymer was 0.5 mg/l for alum. These coagulant and polymer dosages were retested in subsequent jar tests in the laboratory using raw water at 19°C and 5°C, respectively.

Coagulation flocs were collected from each jar and stabilized in an agar solution on petri dishes. The process of agar sample preparation is presented in section 3.3.2. The microscopic analysis is discussed in the next chapter.

3.2.2 Coagulation jar tests in the laboratory at 5ºC

In order to investigate the effect of temperature on alum and PACl performance, a series of bench-scale jar tests with alum and PACl combined with polymer and PAC was conducted using the raw water at different temperatures. One 20-L tank of raw water sample was delivered from Split Lake to the Environmental Engineering Laboratory at the University of Manitoba in September 2002. It was divided into two clean containers. One 5-L container of the raw water was used for jar tests at room temperature the next day. One 15-L container of the raw water, stored in a refrigerator, was used for jar tests at 5ºC after 2 days.

Prior to the jar tests, the initial parameters of raw water such as temperature, pH, alkalinity, turbidity and colour were measured. The results, presented in Table 3-3, showed that the quality of raw water in September was similar to that tested on site in August.

Based on the results of the jar tests on site, alum and PACl combined with polymer and PAC were tested at the selected dosages at different temperatures. The results of treated water are presented in Appendix B. The settled aggregated flocs in each jar were collected and stabilized by embedding them in solidified agar for further microscopic analysis.

Table 3-3 Split Lake raw water quality (Aug. and Sept. 2002)

Sample Date	Temperature (ºC)	Turbidity (NTU)	Colour (TCU)	pH	Alkalinity mg $CaCO_3$/l
Sept. 2002	18	38	70	7.4	84
Aug. 2002	19	44	70	7.7	89

3.3 Microscopic flocs analysis

There is growing interest in the coagulation flocs analysis in water treatment. This is because the performance of coagulation, sedimentation, filtration and disinfection processes in water treatment system is strongly influenced by the coagulation flocs. In order to understand the factors affecting the size of coagulation flocs, microscopic particles analysis were conducted.

3.3.1 Slide sample preparation

A few drops of raw water were required to make a slide sample for microscopic analysis. The particle concentration was too low to get representative data of particles in the few drops of the analyzed water sample. The following measures had to be taken to increase the concentration of particles. A 20-L clean container was filled with raw water, set aside and covered for 12 hours. Most of the particles causing water turbidity settled to the bottom of the container during that time. Following the settling period, the water at the top of container was decanted leaving about 2-L of sediment concentrate at the bottom. The sediment concentrate was then transferred to a 2-L beaker and allowed to settle for another 12 hours. Following the second settling period, the water at the top of the beaker was decanted leaving about 100 ml of the concentrate at the bottom. The concentrate sample was centrifuged at 5500 rpm for 10 minutes. The water at the top of the tubes had to be decanted, leaving about 1 ml of concentrated sample at the bottom. A drop of this water sample was placed on a microscope slide. Once dry, the slides were sealed with a slide epoxy for sample preservation (Gorczyca and London, 2003). Two or three such slide preparations were required for further analysis using image analysis software.

3.3.2 Agar sample preparation

3% agar Noble solution was prepared using distilled water. The mix solution was heated in the autoclave at 121 ºC and 1.6 kg/cm^2 for 20 minutes. Then the solution was transferred and stored this solution in a water bath at about 50 ºC. using a wide-mouth pipette, 1 ml of settling flocs was mixed with 8 ml of 3% agar solution in a petri dish. The petri dish was gently rotated immediately after the molten agar is added for uniform distribution of flocs. Thus, the flocs were gradually stabilized in solidified agar with the temperature decrease. The flocs could no longer move to contact with other flocs in the sample. It was demonstrated that flocs prepared in this manner, and stored at 4ºC could be kept up to 7 days without obvious alteration in floc morphology (Ganczarczyk et al., 1992).

3.3.3 Coagulation flocs image analysis

In this study, the geometric characteristics of raw water particles on slide samples and coagulation flocs in agar solidified samples, such as cross-sectional area, perimeter, X/Y coordinate and shape factors, were examined in detail using the Bioquant classic 95 image analysis software. The components of the Bioquant classic 95 image analysis system are illustrated in Figure 3-5. The optical microscope combined with a digital video camera is connected to a computer though a camera adaptor. The morphometric features of the specimen displayed in the overview window on the monitor can be manually traced within the microscope viewing field. The process of particle size measurement using the Bioquant Classic 95 image analysis software is described as follows:

Objective selection: Place the specimen on the stage, use live image function to get the viewing field of slide or agar specimen by adjusting the microscope. Choose a suitable objective to focus the specimen.

System calibration: Replace the specimen with a micrometer on the stage, do calibration for each chosen objective before the particle size measurement.

Image capture: Place the specimen on the stage. Select the image of particles under a chosen objective, use save image in the file menu. Thus, the image observed can be captured and saved in the computer for further analysis and measurement.

Measurement: Use load image to open the saved image of particles. Identify all the particles in view through the colour threshold function. Select topography arrays for the measurement. Choose automatic or manual measurement to measure particles.

Data management: Use data management function to transfer data from *.Tif format to Notepad or Excel format.

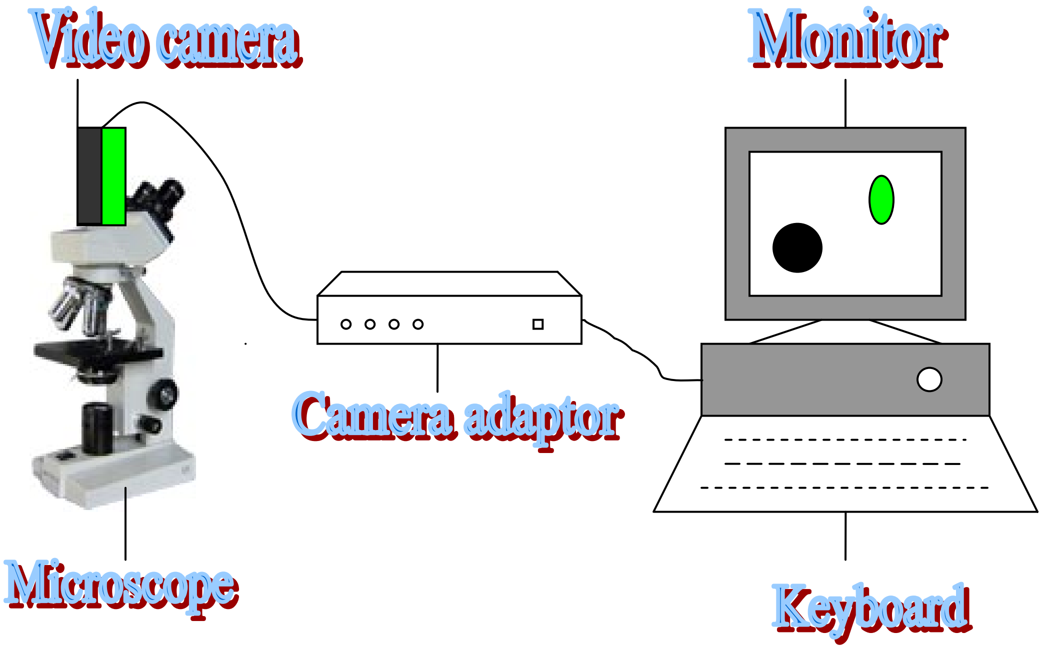

Figure 3-5 Schematic of Bioquant classic 95 image analysis system

The shape factor is an estimate of the amount by which an object varies from a circle; for example, the shape factor for a circle is 1.0 and for a line is 0. This parameter can be calculated by the following equation: Cross-sectional Area

$$\text{Shape factor} = \frac{4 \times \pi \times \text{Cross-sectional Area}}{\text{Perimeter}^2}$$

As well, the equivalent diameter is the diameter of a circle having the projected area as the particle image, and can be calculated by the following equation:

$$\text{Equivalent diameter} = \left(\frac{4 \times \text{Cross-sectional Area}}{\pi} \right)^{0.5}$$

3.3.4 Coagulation flocs size distribution analysis

After the microscopic flocs size measurement, the measured raw data can be further analyzed by using SPSS (Statistical Package for the Social Science) statistical software.

In this study, the graphs of coagulation flocs size distribution (FSD) were plotted and are presented in the next chapter and Appendix C.

Chapter 4 Results Analysis and Discussion

In this chapter, water turbidity and settled alum and PACl coagulation flocs size are analyzed and discussed. These are the two main indices for evaluation of coagulation process.

4.1 Raw water analysis

The slide samples prepared from the centrifuged raw water were initially viewed under a microscope using three different magnifications: 100x, 400x, and 1000x. The images of typical particles are shown in Figures 4-1, 4-2 and 4-3. The main particles in the raw water were mineral particles, filamentous diatoms, and particle aggregates.

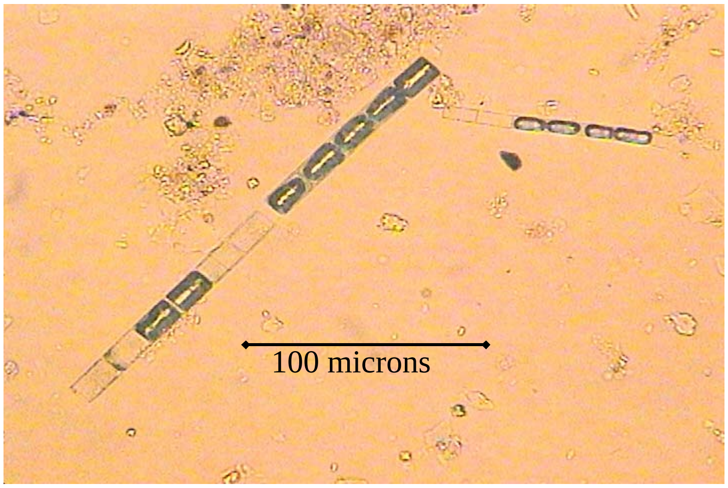

Figure 4-1. Particles suspended in the Split Lake raw water (Diatom)

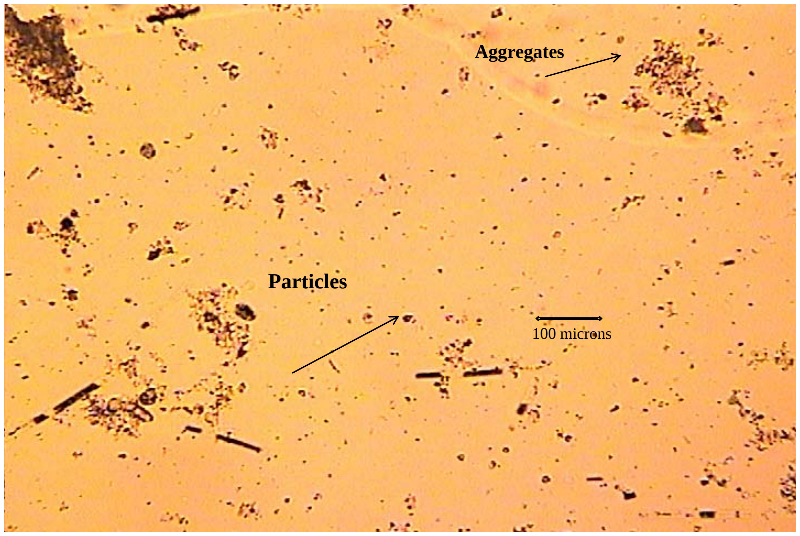

Figure 4-2. Particles suspended in the Split Lake raw water

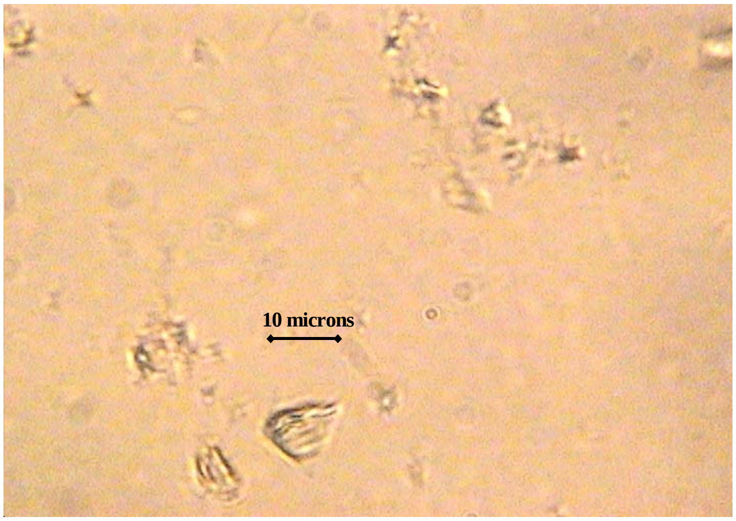

Figure 4-3. Particles suspended in the Split Lake raw water (Mineral particles)

Most particles in the Split Lake raw water could be seen under 400x magnification. Hence, the particles on each slide were measured under this magnification. The PSD results, shown in Figure 4-4, indicated that 99% of the particles were smaller than 10µm, with a mean value of 2.3µm. Based on the appearance and size of the particles, algae and clay particles were found to be the main particles in the raw water.

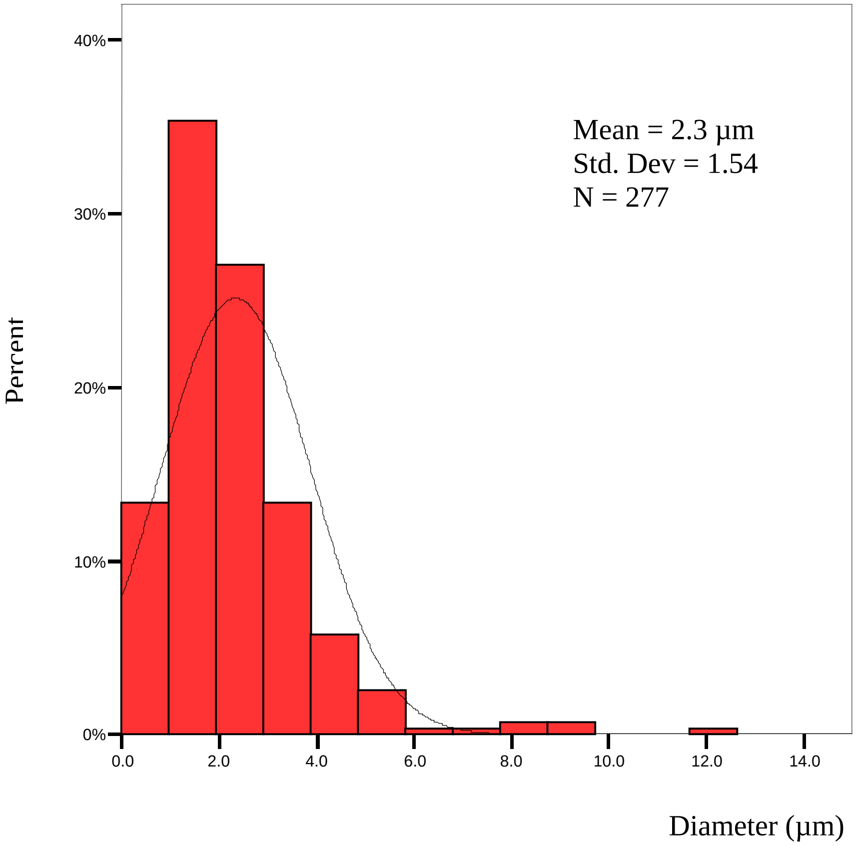

Figure 4-4. Particle size distribution of raw water in Split Lake

4.2 Coagulation flocs analysis

Initial coagulation flocs samples were prepared on site at the Split Lake WTP by mixing settled coagulation flocs with an agar solution in a petri dish. These flocs images were not ideal due to a poorly dissolved agar solution melted on a hot plate. Coagulation flocs samples prepared with agar dissolved in autoclave in the lab at the University of Manitoba were clear, and were used for further microscopic analysis in this study.

Alum and PACl coagulation flocs samples prepared in the lab were viewed under a microscope using 10x and 40x magnifications. Most flocs could be identified with 10x objective magnification. Hence, coagulation flocs in each petri dish were measured under this magnification. The images of typical alum and PACl coagulation flocs are shown in Figures 4-5 and 4-6. Although many alum and PACl coagulation flocs were observed under a microscope, the difference between alum flocs and PACl flocs could not be found with the naked eye. Therefore, alum and PACl flocs size distributions are plotted in Figures 4-7, 4-8, 4-9 and 4-10 for further analysis.

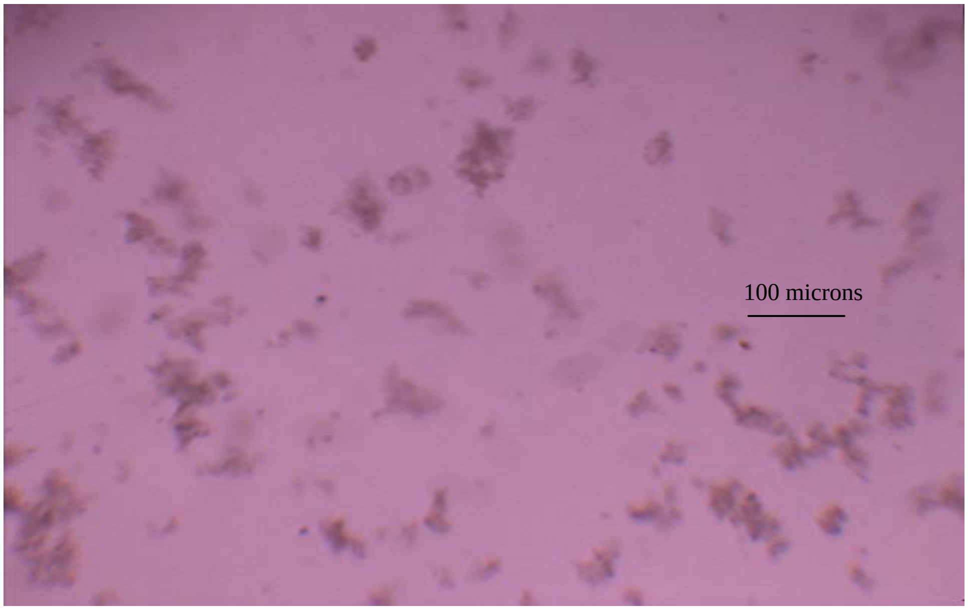

Figure 4-5 Alum coagulation flocs embedded in agar at 5ºC

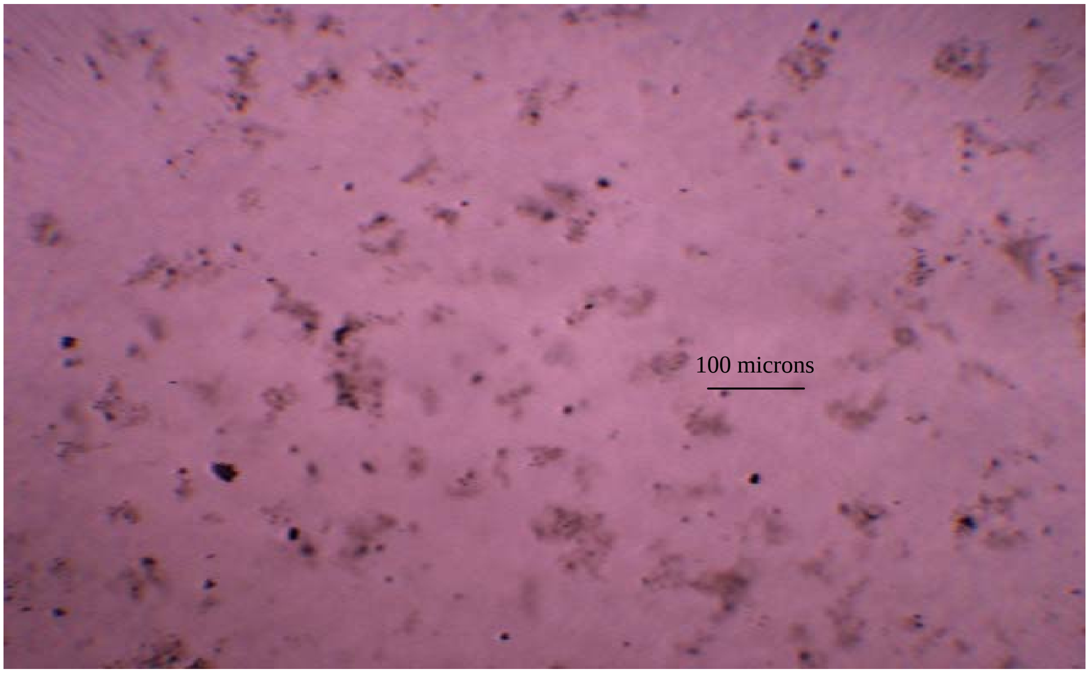

Figure 4-6 PACl coagulation flocs embedded in agar at 5ºC

Fig.4-7 Flocs size distribution at alum dosage of 100 mg/l at 19ºC

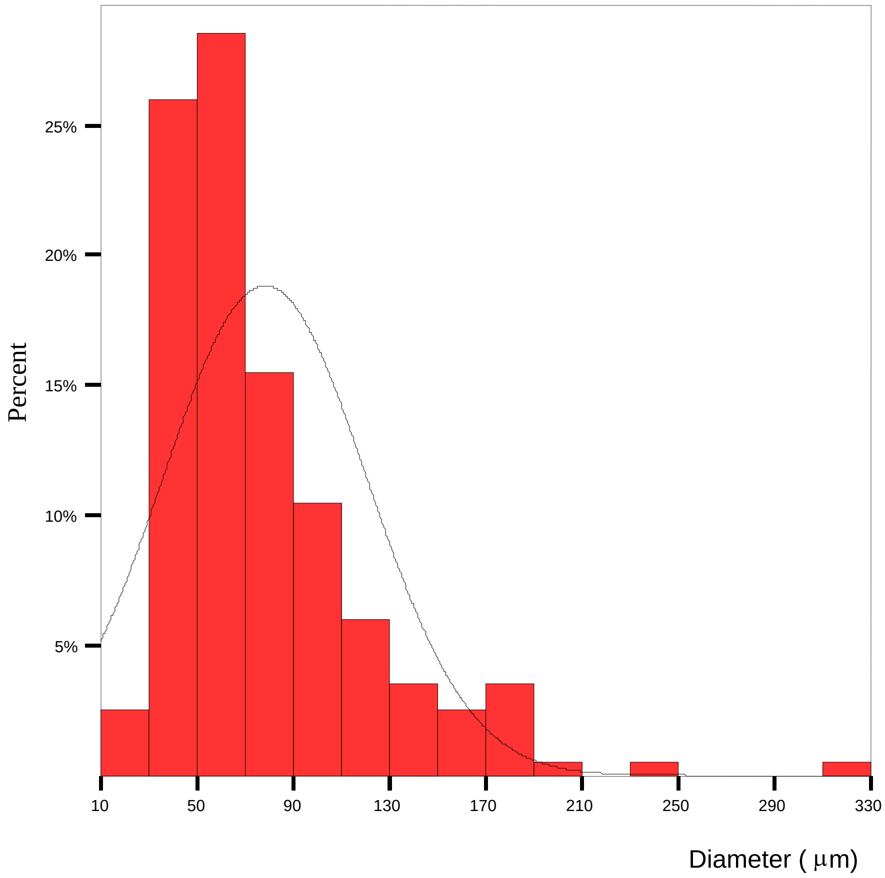

Table 4-1 Flocs size distribution data at alum dosage of 100 mg/l at 19ºC

Mean (µm)		104.3
Std. Deviation		42.4
Kurtosis		5.4
Minimum		25.5
Maximum		312.7
Percentiles	5	31.9
	10	38.7
	30	52.5
	50	67.6
	80	102.5
	90	134.4
	95	172.2

Fig. 4-8 Flocs size distribution at PACl dosage of 84 mg/l at 19ºC

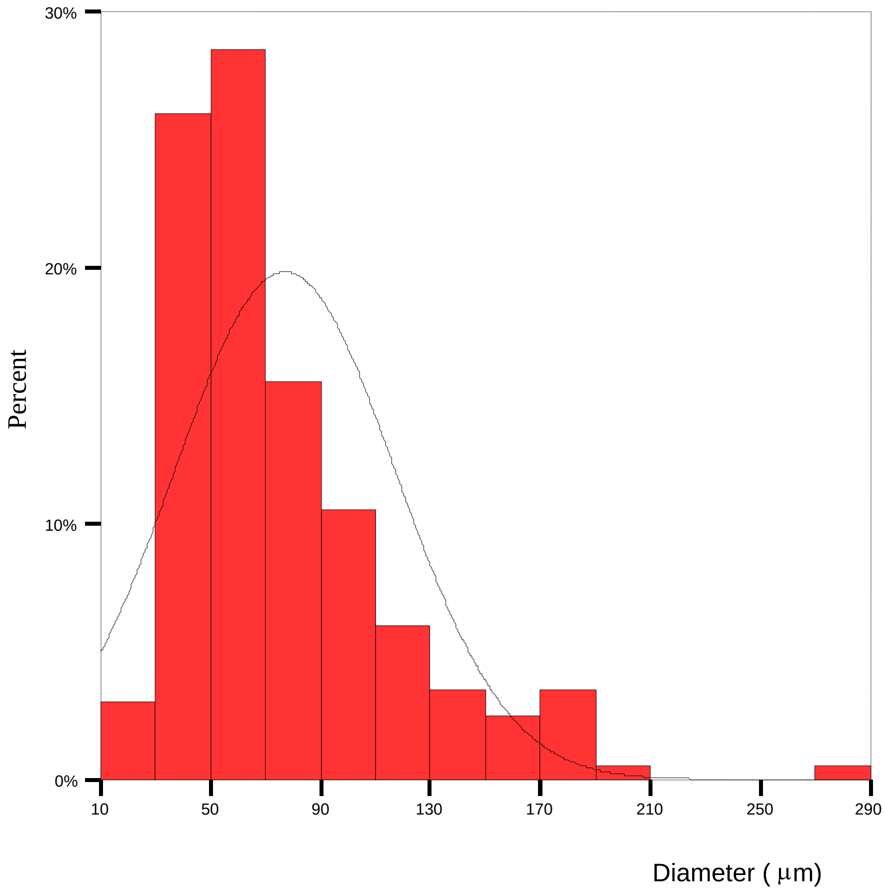

Table 4-2 Flocs size distribution data at PACl dosage of 84 mg/l at 19ºC

Mean (µm)		78.0
Std. Deviation		40.3
Kurtosis		3.9
Minimum		12.2
Maximum		286.2
Percentiles	5	31.9
	10	38.0
	30	52.3
	50	67.6
	80	102.2
	90	132.8
	95	163.3

Fig. 4-9 Flocs size distribution at alum dosage of 100 mg/l at 5ºC

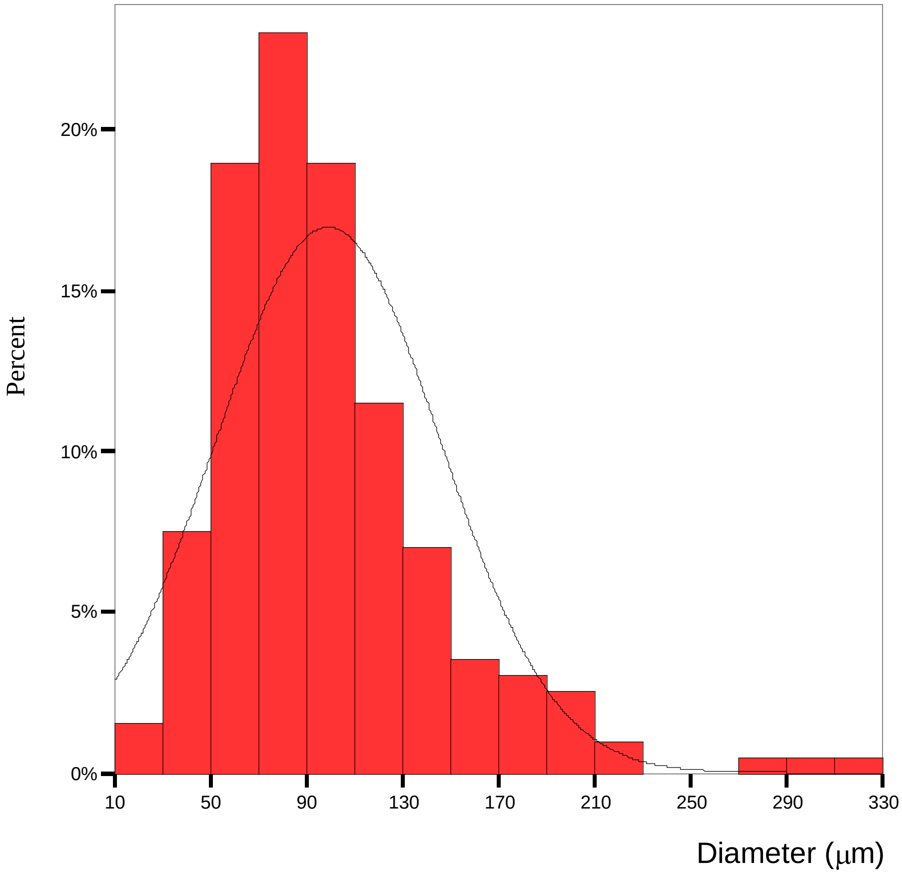

Table 4-3 Flocs size distribution data at alum dosage of 100 mg/l at 5ºC

Mean (μm)		82.5
Std. Deviation		47.0
Kurtosis		4.1
Minimum		24.9
Maximum		316.6
Percentiles	5	46.0
	10	51.0
	30	71.2
	50	89.0
	80	126.1
	90	162.0
	95	190.9

Fig. 4-10 Flocs size distribution at PACl dosage of 84 mg/l at 5ºC

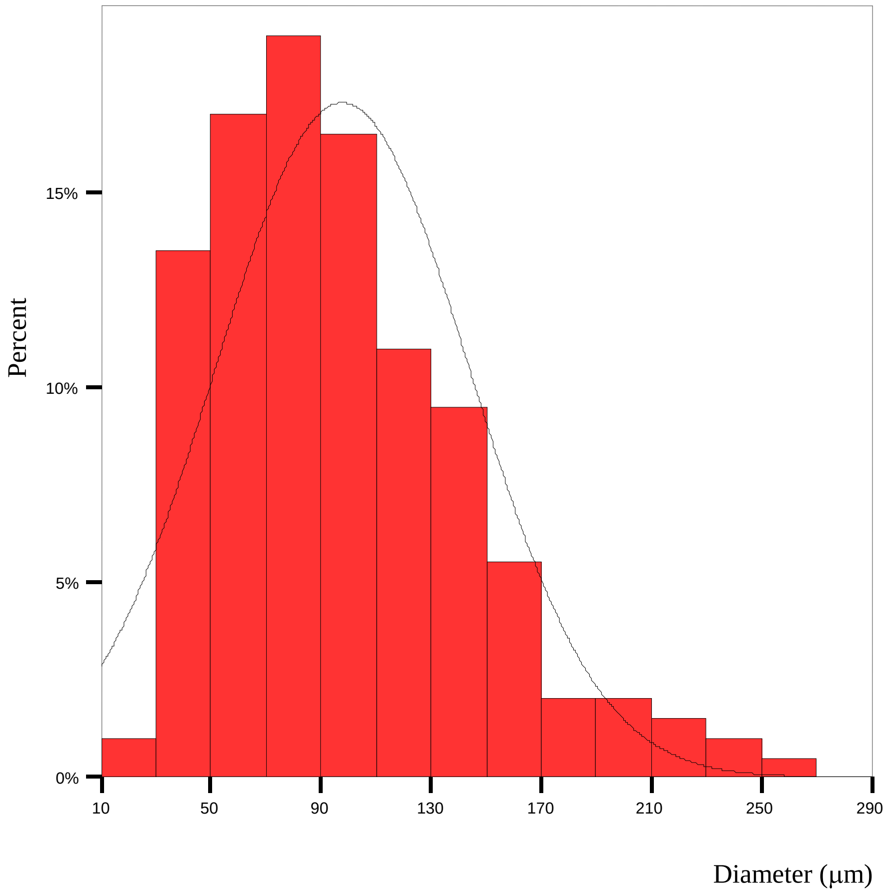

Table 4-4 Flocs size distribution data at PACl dosage of 84 mg/l at 5ºC

Mean (µm)		81.7
Std. Deviation		46.1
Kurtosis		1.8
Minimum		17.9
Maximum		257.1
Percentiles	5	33.5
	10	44.5
	30	68.8
	50	89.0
	80	134.5
	90	161.8
	95	192.9

4.2.1 Alum and PACl coagulation flocs sizes and their settling properties

For the purpose of further discussion and analysis, settled water turbidity, flocculation time and coagulation flocs size are summarized in Table 4-5.

Table 4-5 Alum and PACl coagulation jar tests results

Chemicals	T = 19°C		T = 5°C		Flocculation time (min.)
	Turbidity (NTU)	Mean of flocs size (µm)	Turbidity (NTU)	Mean of flocs size (µm)	
PACl 84	1.2	78	1.3	82	15
PACl 84+Polymer 0.5	1.1	89	1.2	85	
PACl 84+Polymer 0.5+PAC3	1.5	103	1.6	96	
Alum 100	1.5	104	1.8	83	30
Alum 100+Polymer 0.5	1	106	1.1	98	
Alum 100+Polymer 0.5+PAC3	1.9	114	2.1	99	

It is obvious that the average size of alum and PACl coagulation flocs was different. When 100 mg/l alum was used, the settled coagulation flocs size was 104µm at 19ºC and 83µm at 5ºC; When 100 mg/l alum and 0.5 mg/l polymer were used, the settled coagulation flocs size was 106µm at 19ºC and 98µm at 5ºC; When 100 mg/l alum, 0.5 mg/l polymer and 3 mg/l PAC were used, the settled coagulation flocs size was 114µm at 19ºC and 99µm at 5ºC. In contrast, the settled PACl 84 flocs size was 78µm at 19ºC and 82µm at 5ºC. When 84 mg/l PACl and 0.5 mg/l polymer were used, the settled coagulation flocs size was 89µm at 19ºC and 85µm at 5ºC; When 84 mg/l PACl, 0.5 mg/l polymer were used, the settled coagulation flocs size was 89µm at 19ºC and 85µm at 5ºC; When 84 mg/l PACl and 0.5 mg/l polymer and 3 mg/l PAC were used, the settled coagulation flocs size was 103µm at 19ºC and 96µm at 5ºC. Relatively speaking, PACl flocs size was smaller than alum flocs size.

From Table 4-5 we can see that the settling properties of PACl flocs and alum flocs were also different. When 84 mg/l PACl was added to the sample water, the turbidity decreased to 1.2 NTU (1.3 NTU) after 15 minutes of flocculation at 19ºC (5ºC). In contrast, when 100 mg/l alum was added to the sample water, the turbidity decreased to1.5 NTU (1.8NTU) after 30 minutes of flocculation at 19ºC (5ºC). Low water turbidity and small PACl flocs were achieved within shorter flocculation time by less PACl consumption. This indicates that the settling properties of PACl flocs were superior to alum flocs. As discussed previously, Al_{13}^{7+} polymeric aluminium species, the predominant species for PACl flocs formation, have higher density than the monomeric aluminium species. Hence, the density of PACl flocs formed by Al_{13}^{7+} polymeric species could be higher than that of alum flocs with monomeric species. PACl flocs size was smaller than alum flocs size, but the settled water turbidity was lower using PACl than using alum. This indicates that the number of settled PACl flocs was higher than that of settled alum flocs. The density and number of coagulation flocs were not measured in this study. Further research on density and number of alum and PACl flocs is recommended.

In addition, the solubility of PACl is always higher than that of alum. This should be another reason why the settling properties of PACl flocs were superior to those of alum flocs.

4.2.2 The impacts of temperature on alum and PACl flocs sizes

From Table 4-5 we can see that the average size of alum flocs decreased from 104µm at 19ºC to 83µm at 5ºC. This is most likely due to the decreased concentration of monomeric species in alum aqueous solution at the lower temperature. This may be the reason why alum performance was poor at 5ºC, and required a higher alum dosage, the addition of polymer, and longer flocculation time to promote flocs formation. When polymer was used at 5ºC, the size of alum flocs increased from 83µm to 98µm, and the turbidity decreased from 1.8 NTU to 1.1 NTU.

In contrast, PACl flocs did not seem to be affected by the cold temperature. From Table 4-5 we can see that the average size of PACl flocs was 78µm at 19ºC and 82µm at 5ºC, respectively. The difference of PACl flocs size was not significant at 19ºC and 5ºC. As mentioned previously, low water temperature could increase water viscosity and retard the kinetics of the hydrolysis reactions. However, Al_{13}^{7+} polymeric aluminium species with a high charge and high molecular weight are more active than monomeric aluminium species.

The effect of polymer on PACl performance was less significant than that on alum performance. From Table 4-5 we can see that both turbidity and PACl flocs size changed only slightly when polymer was used at 19ºC and 5ºC.

Chapter 5 Summary and Conclusions

In this research, a series of bench-scale jar tests with various coagulants and coagulant aids was conducted with synthetic water and natural Split Lake raw water. The properties of alum and PACl coagulation flocs were investigated for evaluation of coagulant performances at 19ºC and 5ºC for the Split Lake WTP.

Based on the results of the above analysis, the following conclusions may be drawn:

1. The average size of PACl flocs was relatively smaller than that of alum flocs. Settled water turbidity was always better for PACl coagulation. Therefore, the number of settled PACl flocs could be higher than that of settled alum flocs.

2. The settling properties of small PACl flocs were superior to those of large alum flocs, especially at the lower temperature. This indicates that the density of PACl flocs could be higher than that of alum flocs.

3. Alum flocs decreased in size at 5ºC. This is most likely due to the existence of monomeric aluminium species in alum aqueous solution.

4. PACl flocs size did not change significantly at 5ºC. This may be due to the existence of Al_{13}^{7+} polymeric aluminium species in PACl aqueous solution.

Al_{13}^{7+} polymeric aluminium species with a high charge and high molecular weight is more active than monomeric aluminium species.

Chapter 6 Recommendations

Based on this study, recommendations for future research are made as follows:

1. Water turbidity and settled coagulation flocs were tested and analyzed in this study. Further study should be extended to suspended flocs to find a direct relationship between water turbidity and suspended flocs. The method could be similar to the project of suspended particles analysis undertaken in 2003 for the North End Water Pollution Control Centre in Winnipeg, in which petri dish agar samples were prepared to analyze suspended flocs with sizes larger than 1 µm, and glass slide samples were prepared to analyze suspended flocs with sizes less than 1 µm.
2. Additional jar tests with different natural raw water should be conducted to verify the observations in this study.
3. Measurement of density and number of alum and PACl coagulation flocs should be conducted to confirm the findings of this study.

Chapter 7 Engineering Significance

From an engineering point of view, it is a significant improvement to use PACl instead of alum and polymer for the Split Lake WTP.

As observed in this study, the settling properties of PACl flocs were superior to those of alum flocs. PACl optimum flocculation time of 15 minutes was less than alum optimum flocculation time of 30 minutes. Use of PACl would reduce the size of flocculation tank by up to 50%.

Compared to alum, PACl has more flexible temperature ranges and works well in water without polymer. Thus, the coagulation operation would be controlled more easily using PACl than using alum and polymer. This simple coagulation process is important for plants operated by first nations.

Less PACl dosage consumption results in lower transportation cost. Overall 9.7% saving in costs can be achieved when PACl is used instead of alum and polymer (see Appendix D).

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Appendix A

Synthetic Water Jar Tests Results

Table A-1 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6
Alum, mg/l	20	30	40	50	60	70
Colour, TCU	40	20	10	10	10	10
Turbidity, NTU	9.80	3.50	1.90	1.00	1.10	1.35
pH	6.85	6.65	6.60	6.50	6.45	6.45
0.02N H_2SO_4	2.70	2.30	2.10	1.70	1.60	1.60
Alkalinity, mg $CaCO_3$/l	54	46	42	34	32	32

Table A-2 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6
PACl, mg/l	12	24	36	48	60	72
Colour, TCU	25	20	10	10	5	5
Turbidity, NTU	8.90	3.90	0.88	0.65	0.55	0.60
pH	7.05	7.00	6.90	6.85	6.80	6.80
0.02N H_2SO_4	2.80	2.75	2.60	2.60	2.60	2.60
Alkalinity, mg $CaCO_3$/l	56	55	52	52	52	52

Table A-3 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6
Sumalchlor 780, mg/l	13	26	39	52	65	78
Colour, TCU	20	10	10	5	5	5
Turbidity, NTU	7.90	2.00	1.10	1.00	0.90	1.10
pH	7.05	7.00	6.90	6.80	6.70	6.75
0.02N H_2SO_4	2.85	2.80	2.65	2.50	2.45	2.50
Alkalinity, mg $CaCO_3$/l	57	56	53	50	49	50

Table A-4 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6
Sumaclear 50, ml	13	27	40	54	67	80
Colour, TCU	20	10	10	5	5	10
Turbidity, NTU	7.10	2.20	1.80	1.50	1.90	3.80
pH	7.10	7.05	7.00	6.95	6.95	6.90
0.02N H_2SO_4	2.85	2.85	2.80	2.80	2.70	2.70
Alkalinity, mg $CaCO_3$/l	57	57	56	56	54	54

Table A-5 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6	7
PASS100, mg/l	26	40	53	66	79	92	106
Colour, TCU	20	10	10	10	10	20	20
Turbidity, NTU	4.5	2.2	1.9	1.5	1.2	6.5	6.9
pH	7.1	7	7	6.9	6.85	7	6.9
Alkalinity, mg $CaCO_3$/l	56	54	54	52	52	54	52

Table A-6 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6	7
$FeCl_3$, mg/l	26	40	53	66	79	132	174
Colour, TCU	40	35	30	25	20	15	10
Turbidity, NTU	11	8.4	6.2	4.7	2.5	1	1
pH	6.85	6.9	6.95	6.95	6.9	6.1	6
Alkalinity, mg $CaCO_3$/l	52	52	53	53	52	34	33

Table A-7 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6	7
AluFer C, mg/l	27	41	54	68	81	95	108
Colour, TCU	30	25	20	20	10	10	10
Turbidity, NTU	11	6	4.7	4	2.7	1.8	1.2
pH	6.9	6.9	6.7	6.7	6.65	6.45	6.4
Alkalinity, mg $CaCO_3$/l	52	52	48	48	46	36	36

Table A-8 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6	7
Alum, mg/l	50						
Polymer, mg/l	1	2	3	4	5	6	26
Colour, TCU	5						
Turbidity, NTU	0.65	0.5	0.4	0.54	0.48	0.55	0.99
pH	6.35	6.3	6.5	6.5	6.4	6.35	6.35
Alkalinity, mg $CaCO_3$/l	37	37	38	38	36	36	36

Table A-9 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6	7
PACl, mg/l	36						
Polymer, mg/l	0.5	1	2	3	4	5	6
Colour, TCU	5						
Turbidity, NTU	0.58	0.36	0.35	0.33	0.32	0.35	0.48
pH	6.9	6.9	7	7.05	7.15	6.9	7.05
Alkalinity, mg $CaCO_3$/l	52	52	55	55	58	52	55

Table A-10 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6
Alum, ml	50					
Polymer, mg/l	1					
PAC, mg/l	0	3	10	15	20	30
Colour, TCU	5	5	5	5	5	5
Turbidity, NTU	0.65	1	1.05	1.1	1.3	1.8
pH	6.35	6.3	6.3	6.35	6.3	6.5
Alkalinity, mg $CaCO_3$/l	37	36	36	36	36	38

Table A-11 Jar Tests (T = 5°C)

Jar number	1	2	3	4	5	6
PACl, ml	36					
Polymer, mg/l	0.5					
PAC, mg/l	0	3	10	15	20	30
Colour, TCU	5	5	5	5	5	5
Turbidity, NTU	0.58	0.89	1	1.2	1.4	1.9
pH	6.9	7	7	7	7	7.05
Alkalinity, mg $CaCO_3$/l	52	54	54	54	55	55

Table A-12 Jar Tests (T = 5°C)

Jar number	PACl		Alum	
Coagulant, mg/l	36		50	
PAC, mg/l	3			
Polymer, mg/l	0.5		1	
Time, min.	15	30	15	30
Colour, TCU	5	5	5	5
Turbidity, NTU	0.89	1.15	1.2	1.04
pH	7	6.9	6.35	6.3
Alkalinity, mg $CaCO_3$/l	54	52	37	36

Table A-13 Jar Tests (T = 19°C)

Jar number	PACl	Alum
Coagulant, mg/l	36	50
Colour, TCU	10	10
Turbidity, NTU	0.8	0.85
pH	6.9	6.35
Alkalinity, mg $CaCO_3$/l	52	37

Appendix B

Split Lake Raw Water Jar Tests Results

Table B-1 Jar tests (T = 19°C)

Jar number	1	2	3	4	5	6
Alum, mg/l	60	73	80	90	100	110
Colour, TCU	10	10	5	5	5	5
Turbidity, NTU	2.5	2.20	1.80	1.50	1.5	1.2
pH	6.6	6.4	6.35	6.3	6.2	6.2
Alkalinity, mg $CaCO_3$/l	52	42	40	39	35	34

Table B-2 Jar tests (T = 19°C)

Jar number	1	2	3	4	5
PACl, mg/l	48	60	72	84	108
Colour, TCU	10	10	5	5	5
Turbidity, NTU	2.5	2.20	1.80	1.2	1.0
pH	6.6	6.4	6.35	6.3	6.2
Alkalinity, mg $CaCO_3$/l	52	42	40	39	35

Table B-3 Jar tests (T = 19°C)

Jar test	Alum			PACl
Coagulant, mg/l	100	100	100	84
Colour, TCU	5	5	5	5
Polymer, mg/l	0.4	0.5	0.6	0.5
Turbidity, NTU	1.3	1.0	1.1	1.1

Table B-4 Jar tests (T = 5°C)

Jar test	Alum				PACl			
Coagulant, mg/l	73		100		60		84	
Colour, TCU	5		5		5		5	
Polymer, mg/l	0	0.5	0	0.5	0	0.5	0	0.5
Turbidity, NTU	3.4	4.1	1.8	1.1	3.4	2.6	1.3	1.2

Table B-5 Jar tests (T = 5°C)

Jar test	Alum		PACl	
Coagulant, mg/l	73	100	60	84
Colour, TCU	5	5	5	5
Polymer, mg/l	0.5	0.5	0.5	0.5
PAC, mg/l	3	3	3	3
Turbidity, NTU	5.3	2.1	3.7	1.6

Appendix C

Flocs Size Distribution Analysis Results

Fig. C-1 Flocs size distribution at PACl 84 mg/l with polymer 0.5 mg/l at 19°C

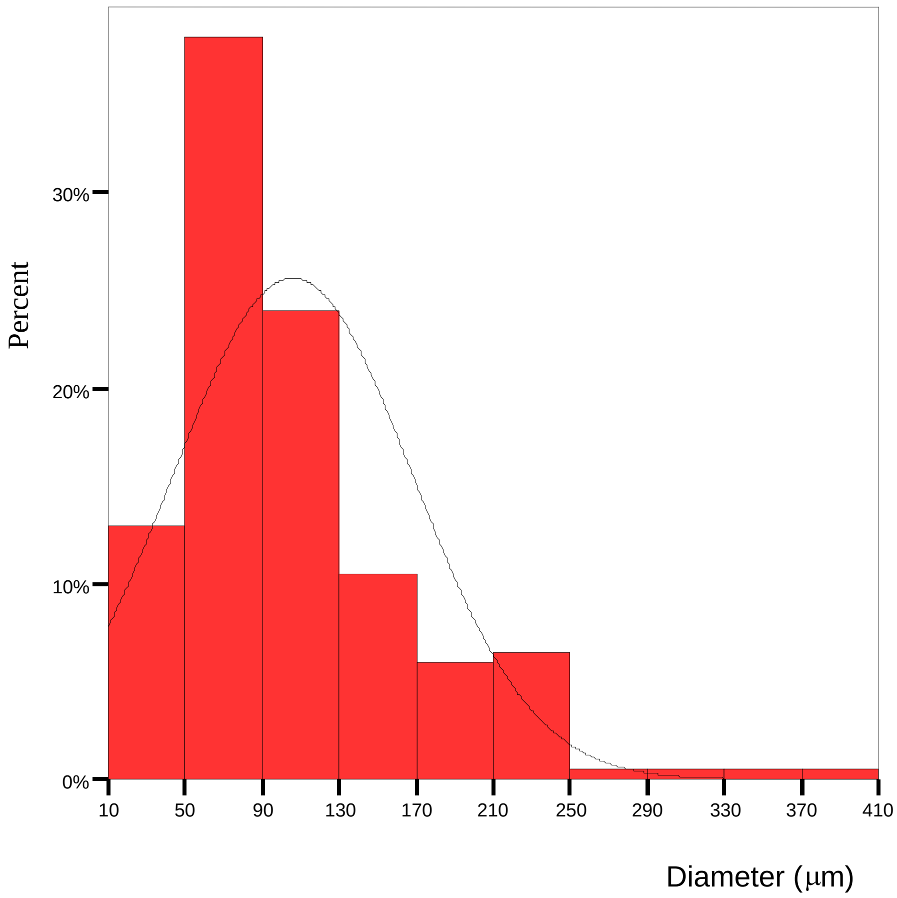

Table C-1 Focs size distribution at PACl 84 mg/l with polymer 0.5 mg/l at 19°C

Mean		89
Std. Deviation		62.2
Kurtosis		2.3
Minimum		26.1
Maximum		371.7
Percentiles	5	41.4
	10	46.9
	30	62.7
	50	88.5
	80	154.7
	90	200.0
	95	235.7

Fig. C-2 Flocs size distribution at PACl 84 mg/l with polymer 0.5 mg/l and PAC 3 mg/l at 19°C

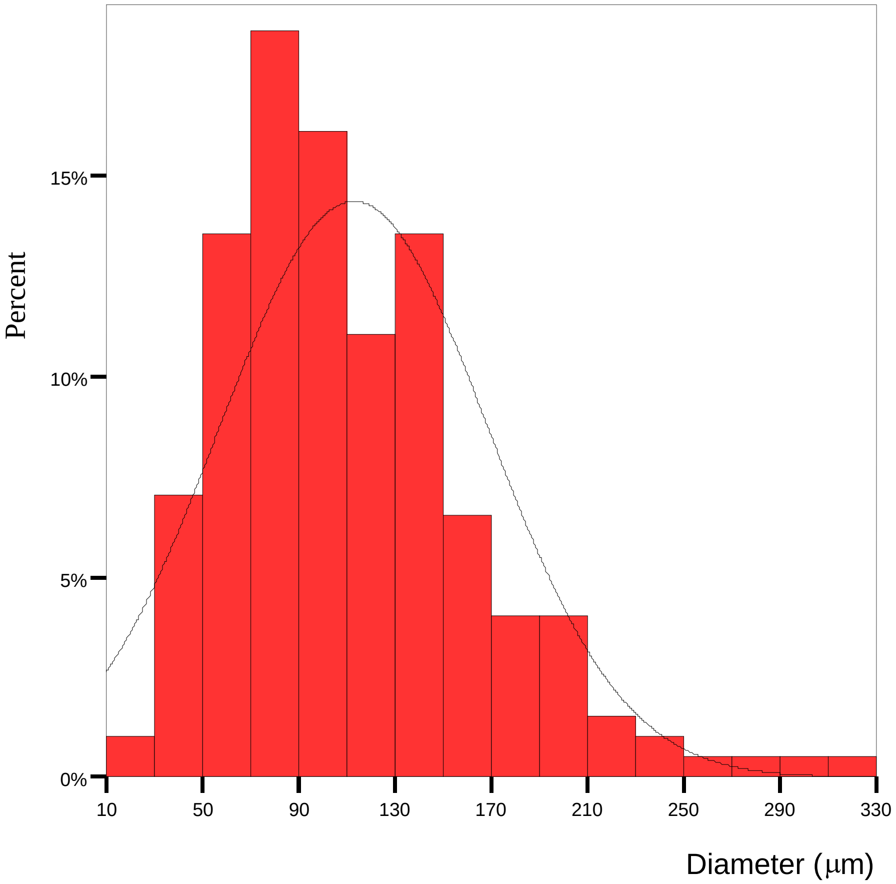

Table C-2 Flocs size distribution at PACl 84 mg/l with polymer 0.5 mg/l and PAC 3 mg/l at 19°C

Mean		103
Std. Deviation		55.9
Kurtosis		3.1
Minimum		27.2
Maximum		329.8
Percentiles	5	41.7
	10	53.9
	30	79.0
	50	103.2
	80	149.6
	90	188.7
	95	212.4

Fig. C-3 Flocs size distribution at alum 100 mg/l with polymer 0.5 mg/l at 19°C

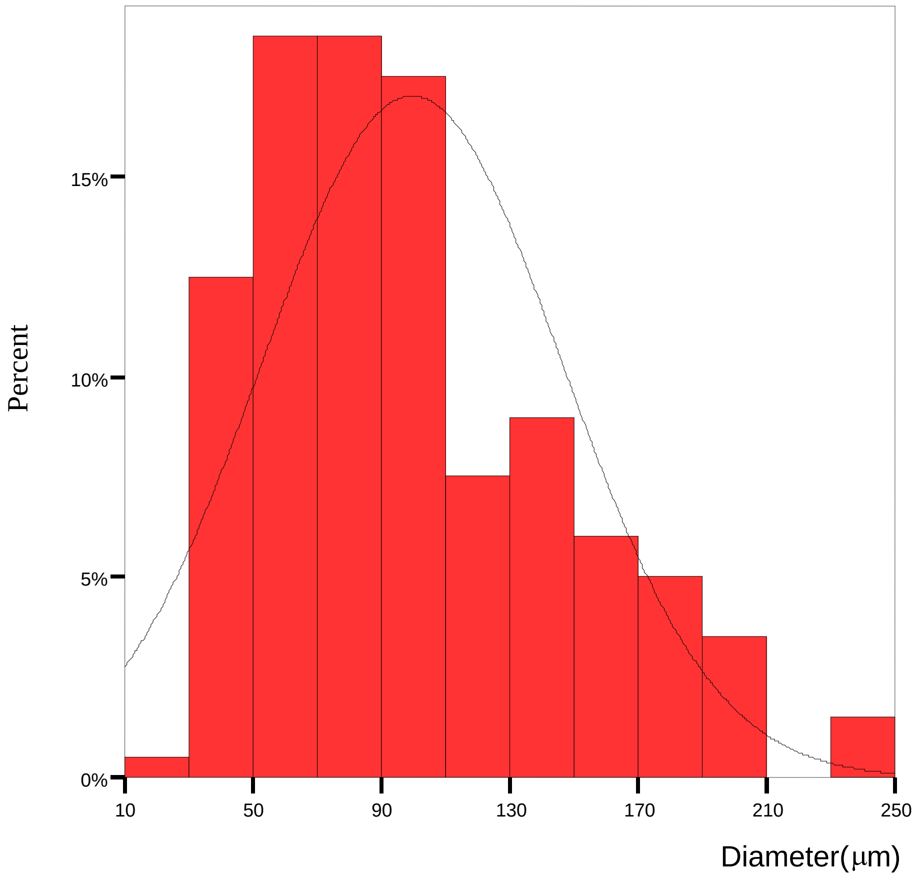

Table C-3 Flocs size distribution at alum 100 mg/l with polymer 0.5 mg/l at 19°C

Mean		106.2
Std. Deviation		46.9
Kurtosis		3.3
Minimum		24.2
Maximum		247.7
Percentiles	5	42.3
	10	46.9
	30	68.7
	50	90.5
	80	139.4
	90	172.2
	95	190.1

Fig. C-4 Flocs size distribution at alum 100 mg/l with polymer 0.5 mg/l and PAC 3 mg/l at 19°C

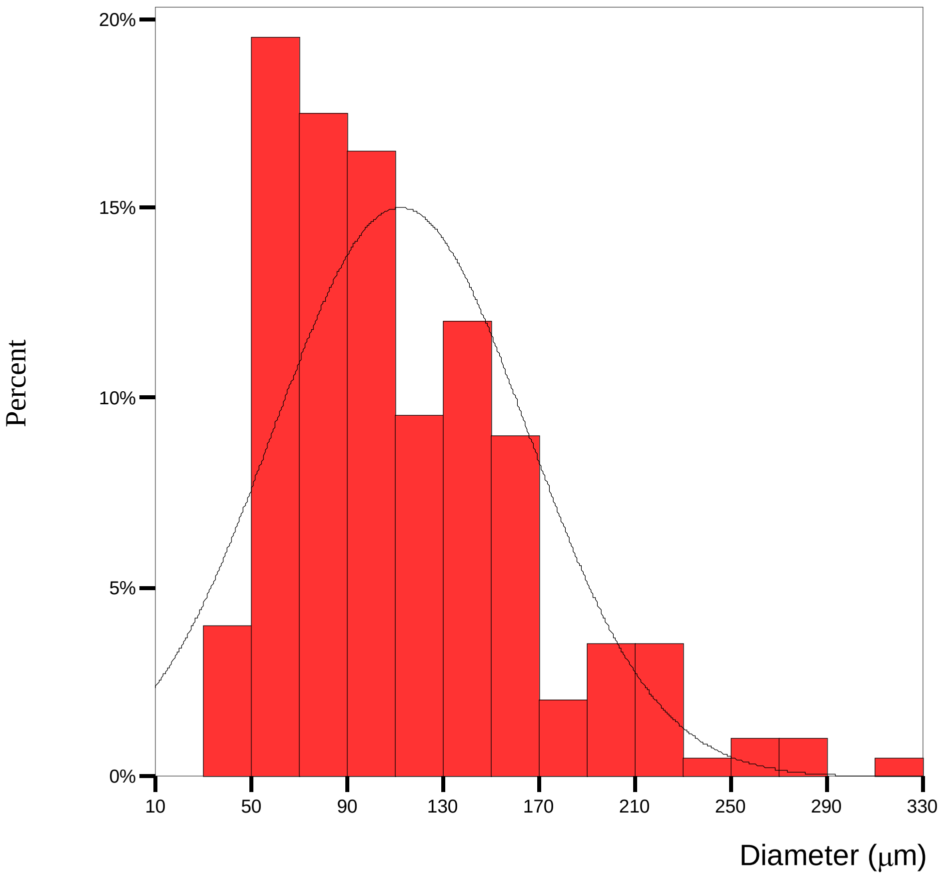

Table C-4 Flocs size distribution at alum 100 mg/l with Polymer 0.5 mg/l and PAC 3 mg/l at 19°C

Mean		113.5
Std. Deviation		53.2
Kurtosis		1.5
Minimum		35.2
Maximum		323.5
Percentiles	5	51.7
	10	56.1
	30	74.6
	50	101.1
	80	151.4
	90	191.1
	95	215.4

Fig. C-5 Flocs size distribution at PACl 60 mg/l at 19°C

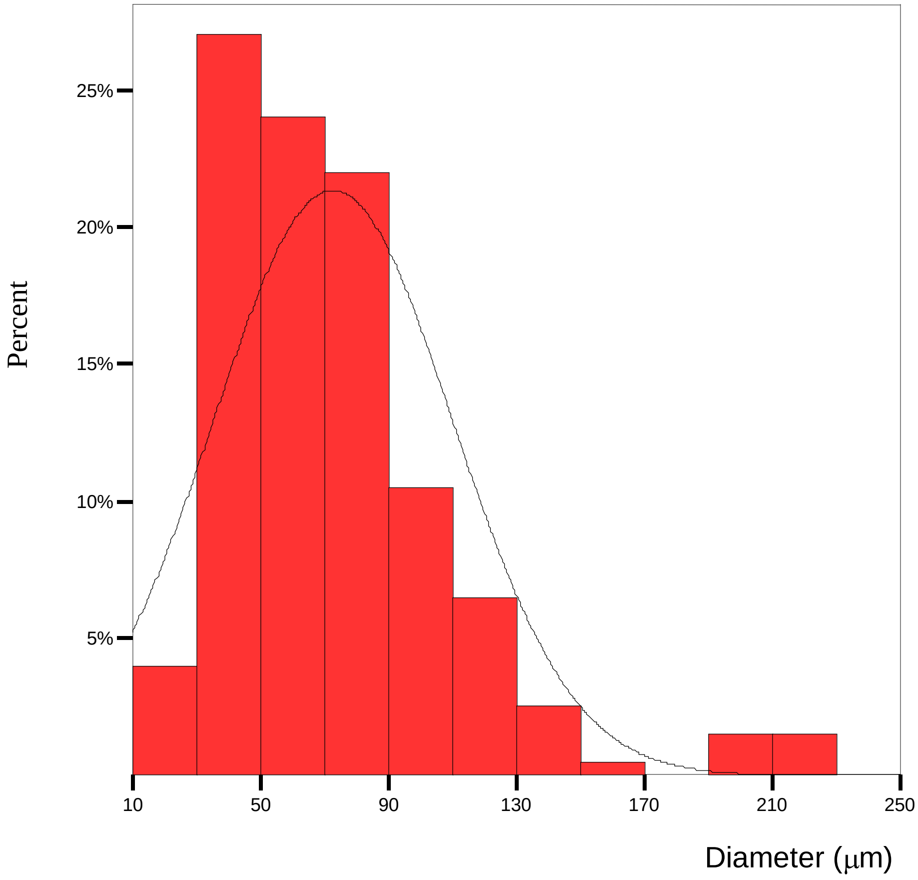

Table B-5 Flocs size distribution at PACl 60 mg/l at 19°C

Mean		73.7
Std. Deviation		37.4
Kurtosis		4.1
Minimum		19.7
Maximum		227.5
Percentiles	5	30.9
	10	35.4
	30	49.4
	50	64.2
	80	94.2
	90	113.9
	95	136.4

Fig. C-6 Flocs size distribution at PACl 60 mg/l with polymer 0.5mg/l at 19°C

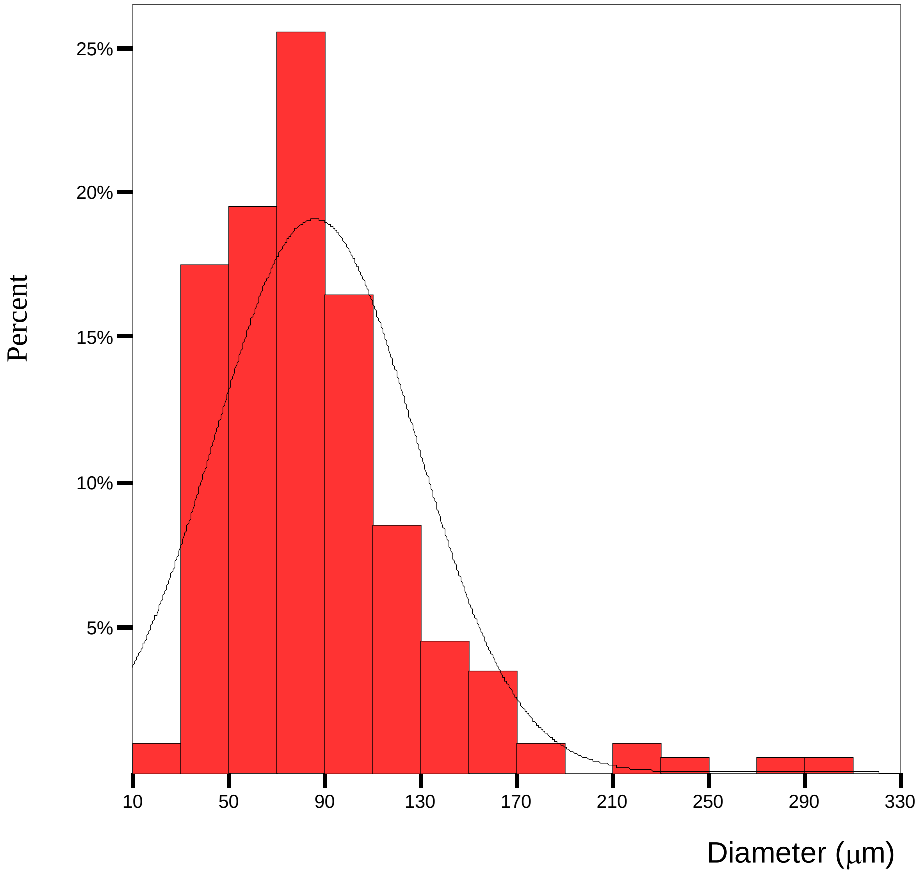

Table C-6 Flocs size distribution at PACl 60 mg/l with polymer 0.5mg/l at 19°C

Mean		88.2
Std. Deviation		41.8
Kurtosis		5.5
Minimum		21.9
Maximum		294.6
Percentiles	5	41.1
	10	43.3
	30	60.8
	50	80.1
	80	110.3
	90	139.0
	95	161.1

Fig. C-7 Flocs size distribution at PACl 60 mg/l with polymer 0.5mg/l and PAC 3 mg/l at 19°C

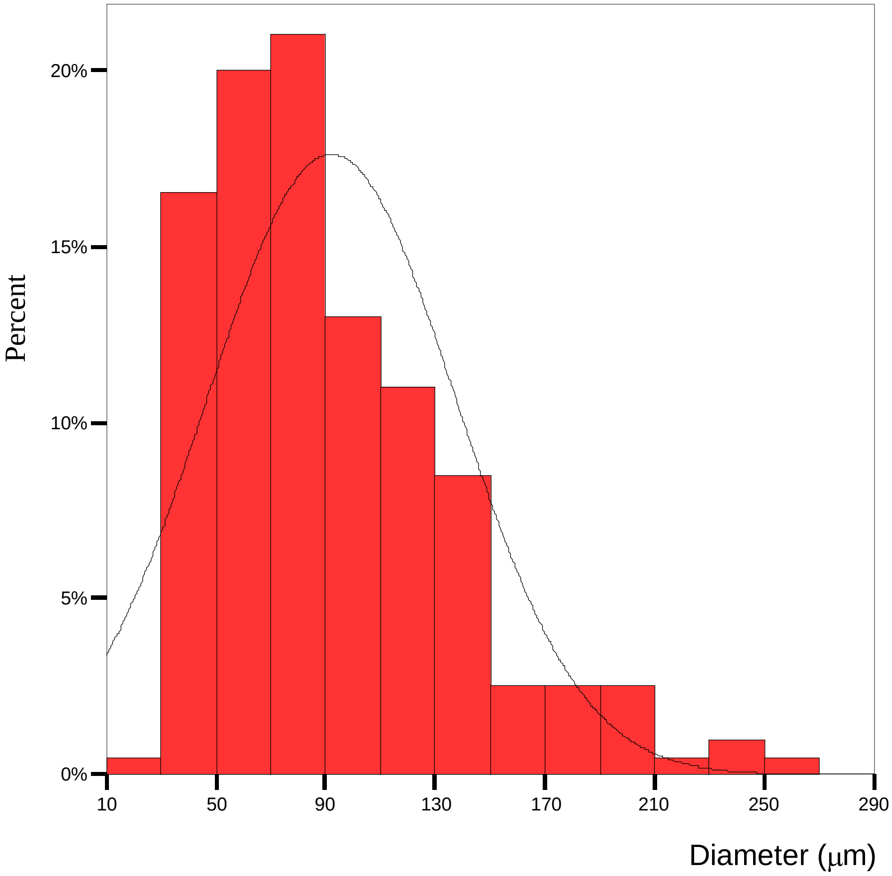

Table C-7 Flocs size distribution at PACl 60 mg/l with polymer 0.5mg/l and PAC 3 mg/l at 19°C

Mean		94.2
Std. Deviation		45.3
Kurtosis		1.6
Minimum		27.2
Maximum		268.7
Percentiles	5	39.0
	10	44.0
	30	62.1
	50	83.4
	80	125.8
	90	149.5
	95	187.4

Fig. C-8 Flocs size distribution at alum 73 mg/l at 19°C

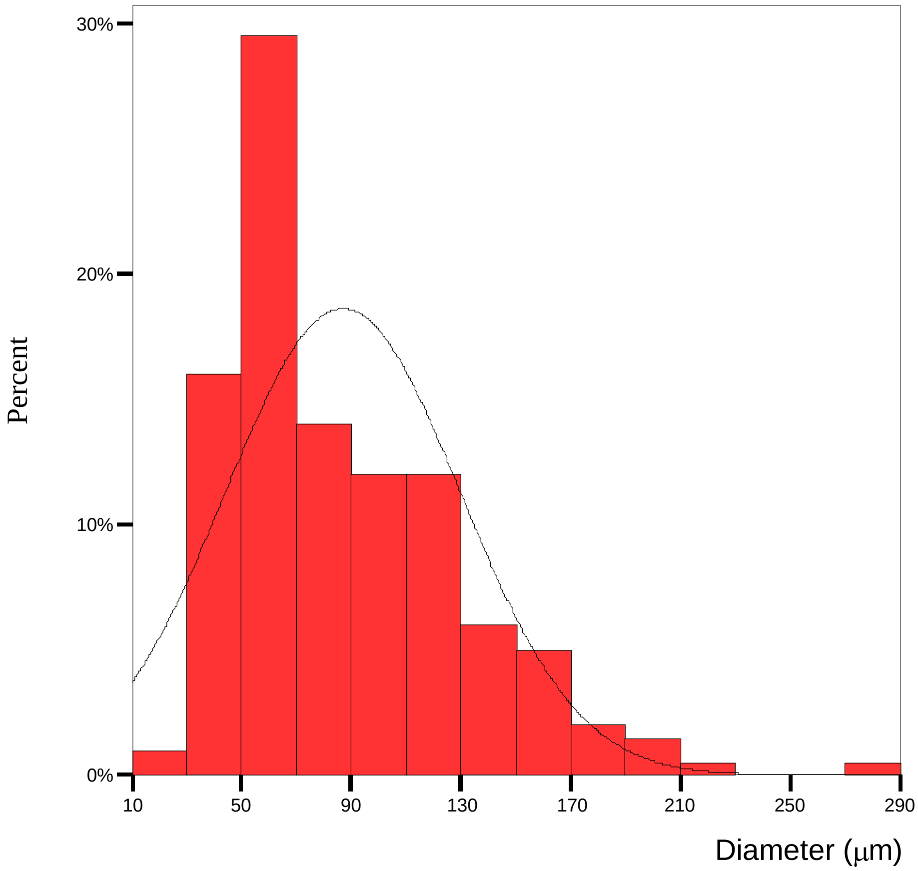

Table C-8 Flocs size distribution at alum 73 mg/l at 19°C

Mean		89.4
Std. Deviation		42.5
Kurtosis		1.6
Minimum		24.3
Maximum		280.1
Percentiles	5	37.5
	10	43.4
	30	58.4
	50	74.4
	80	121.8
	90	148.6
	95	169.3

Fig. C-9 Flocs size distribution at alum 73 mg/l with polymer 0.5 mg/l at 19°C

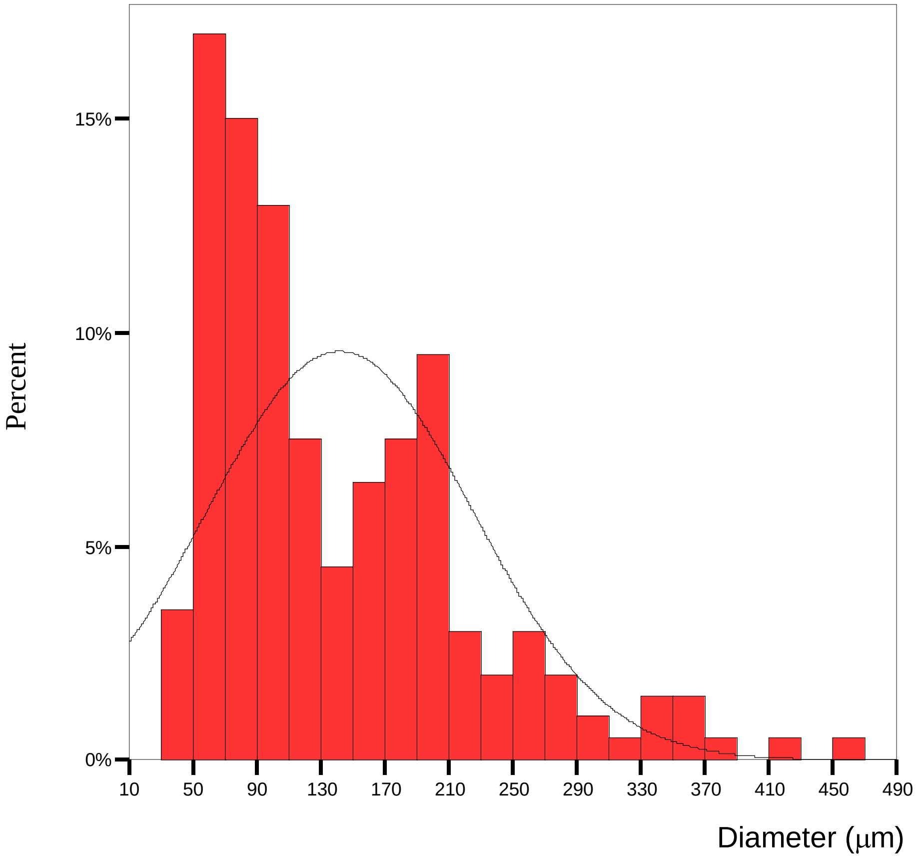

Table C-9 Flocs size distribution at alum 73 mg/l with polymer 0.5 mg/l at 19°C

Mean		121.3
Std. Deviation		83.4
Kurtosis		1.5
Minimum		40.1
Maximum		468.1
Percentiles	5	51.9
	10	56.4
	30	80.8
	50	117.7
	80	201.8
	90	254.1
	95	322.4

Fig. C-10 Flocs size distribution at alum 73 mg/l with polymer 0.5 mg/l and PAC 3 mg/l at 19°C

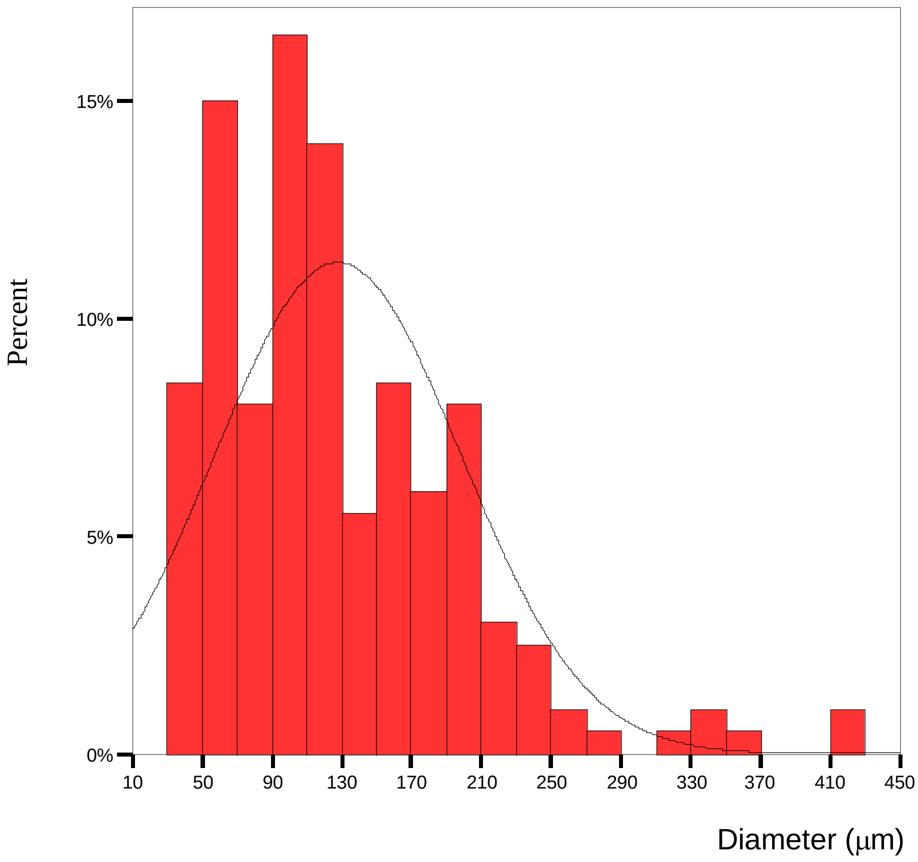

Table C-10 Flocs size distribution at alum 73 mg/l with polymer 0.5 mg/l and PAC 3 mg/l at 19°C

Mean		127.8
Std. Deviation		70. 8
Kurtosis		2.7
Minimum		34.3
Maximum		422.0
Percentiles	5	44.1
	10	51.6
	30	86.3
	50	113.4
	80	186.6
	90	213.6
	95	249.4

Fig. C-11 Flocs size distribution at PACl 84 mg/l with polymer 0.5 mg/l at 5°C

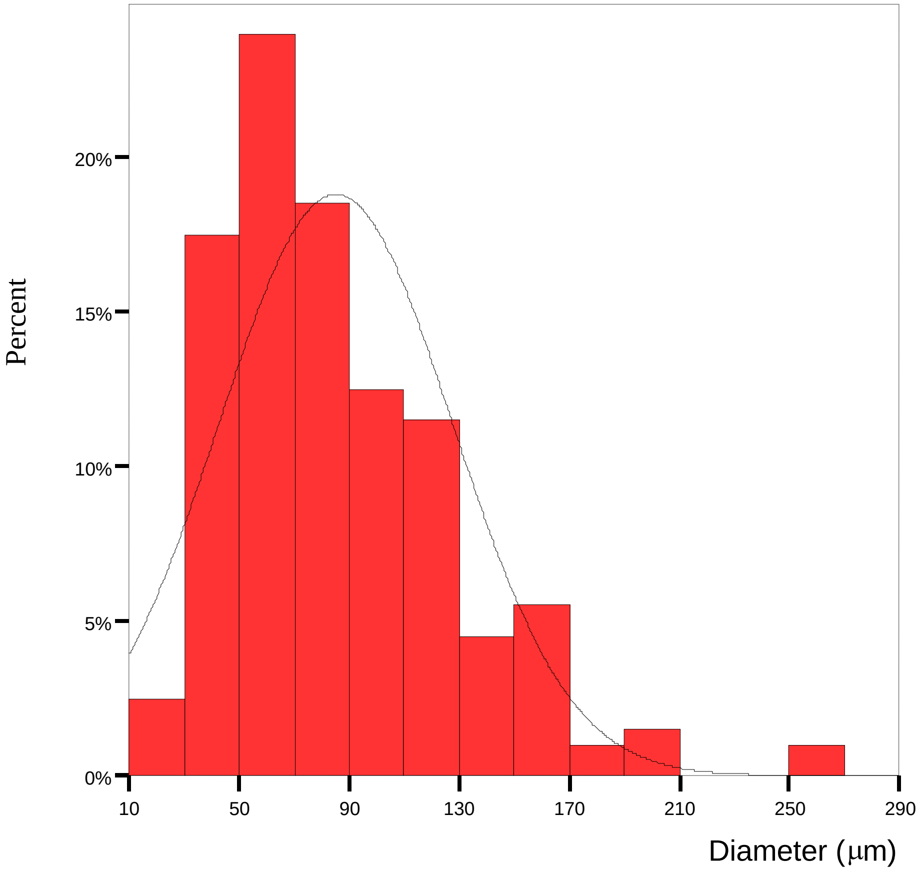

Table C-11 Flocs size distribution at PACl 84mg/l with polymer 0.5 mg/l at 5°C

Mean		85.0
Std. Deviation		42.4
Kurtosis		2.2
Minimum		22.2
Maximum		267.4
Percentiles	5	34.9
	10	40.8
	30	56.3
	50	75.7
	80	119.1
	90	139.6
	95	168.0

Fig. C-12 Flocs size distribution at PACl 84 mg/l with polymer 0.5 mg/l and PAC 3 mg/l at 5°C

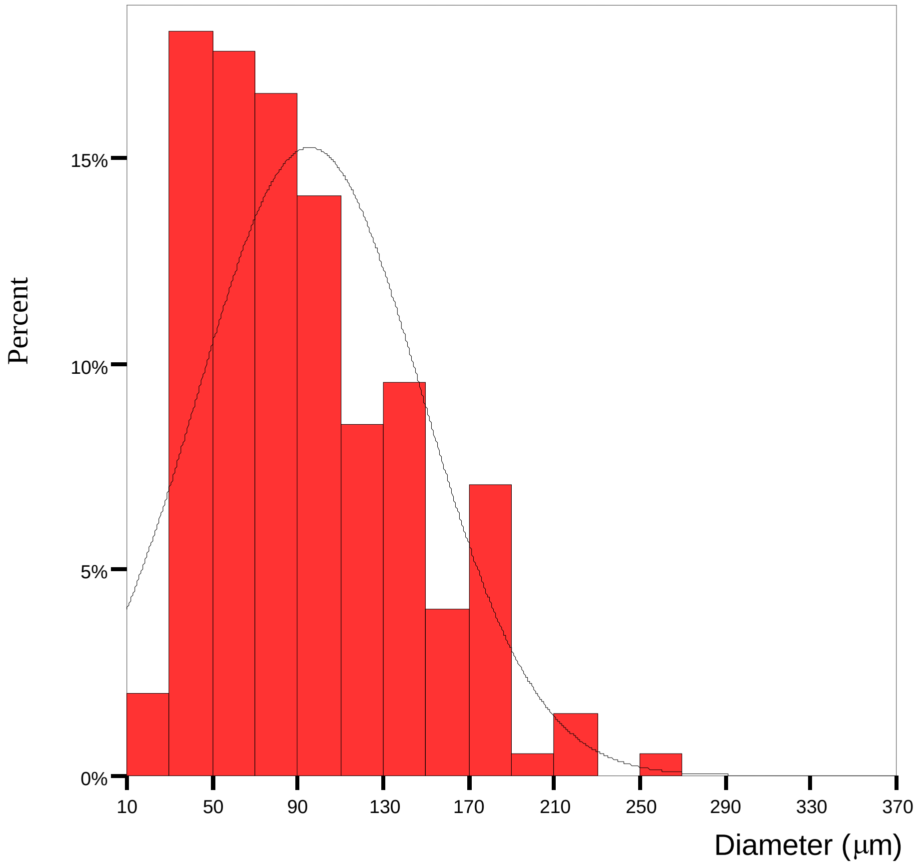

Table C-12 Flocs size distribution at PACl 84 mg/l with polymer 0.5 mg/l and PAC 3 mg/l at 5°C

Mean		95.6
Std. Deviation		52.6
Kurtosis		4.0
Minimum		29.4
Maximum		413.9
Percentiles	5	35.0
	10	41.6
	30	60.0
	50	83.8
	80	140.2
	90	172.1
	95	185.7

Fig. C-13 Flocs size distribution at alum 100 mg/l with polymer 0.5 mg/l at 5°C

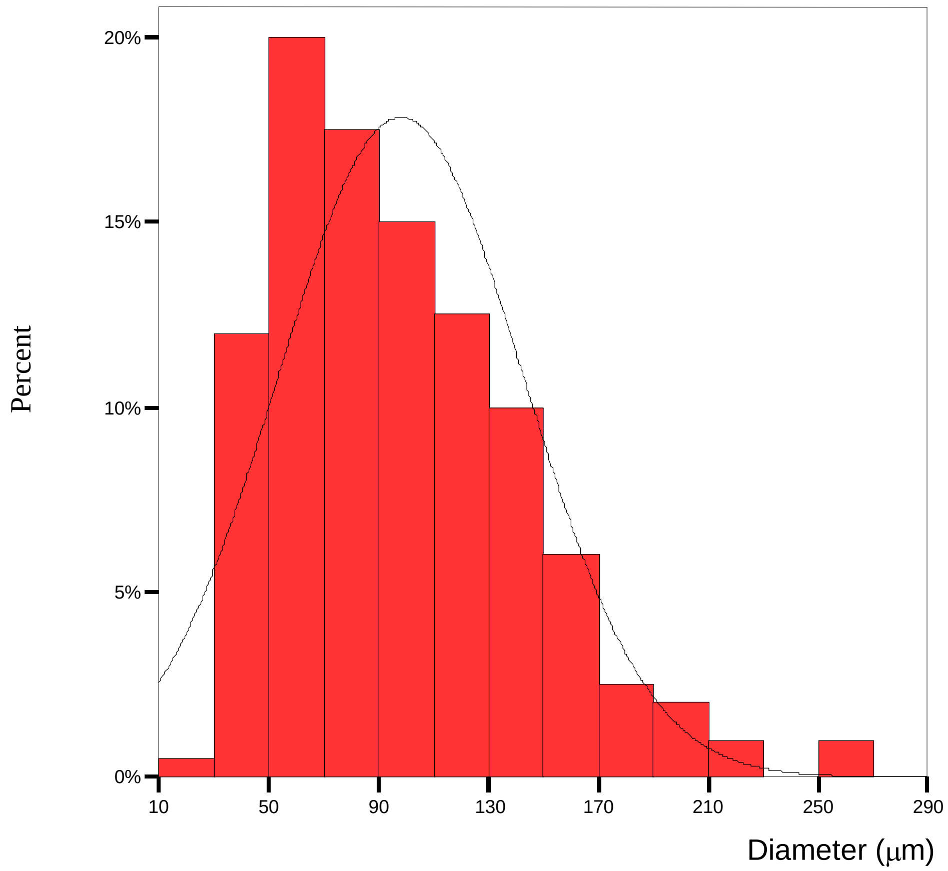

Table C-13 Flocs size distribution at alum 100 mg/l with polymer 0.5 mg/l at 5°C

Mean		98.0
Std. Deviation		44.8
Kurtosis		2.0
Minimum		23.6
Maximum		266.1
Percentiles	5	40.9
	10	46.3
	30	65.2
	50	89.6
	80	135.6
	90	153.5
	95	185.0

Fig. C-14 Flocs size distribution at alum 100 mg/l with polymer 0.5 mg/l and PAC 3 mg/l at 5°C

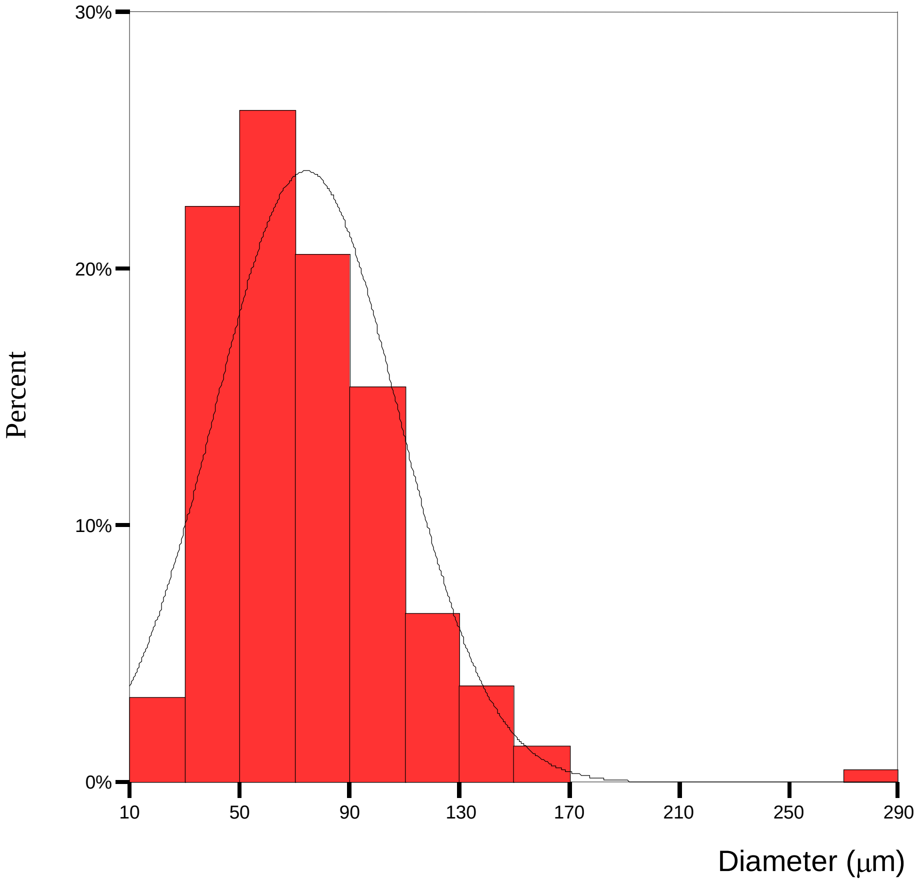

Table C-14 Flocs size distribution at alum 100 mg/l with polymer 0.5 mg/l and PAC 3 mg/l at 5°C

Mean		99.2
Std. Deviation		33.5
Kurtosis		4.0
Minimum		24.9
Maximum		280.6
Percentiles	5	31.7
	10	37.3
	30	54.4
	50	68.5
	80	100.8
	90	115.0
	95	137.8

Fig. C-15 Flocs size distribution at PACl 60 mg/l at 5°C

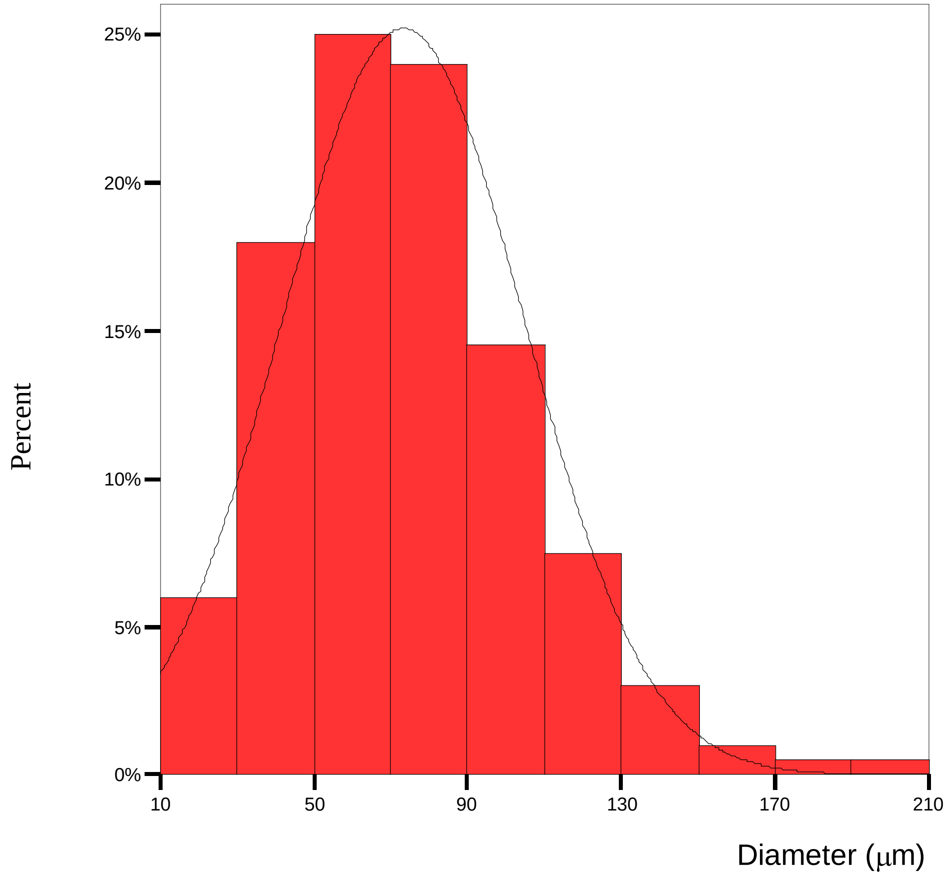

Table C-15 Flocs size distribution at PACl 60 mg/l at 5°C

Mean		73.3
Std. Deviation		31.7
Kurtosis		2.0
Minimum		21.5
Maximum		201.0
Percentiles	5	29.2
	10	34.3
	30	54.6
	50	70.6
	80	101.5
	90	113.7
	95	130.0

Fig. C-16 Flocs size distribution at PACl 60 mg/l with polymer 0.5 mg/l at 5°C

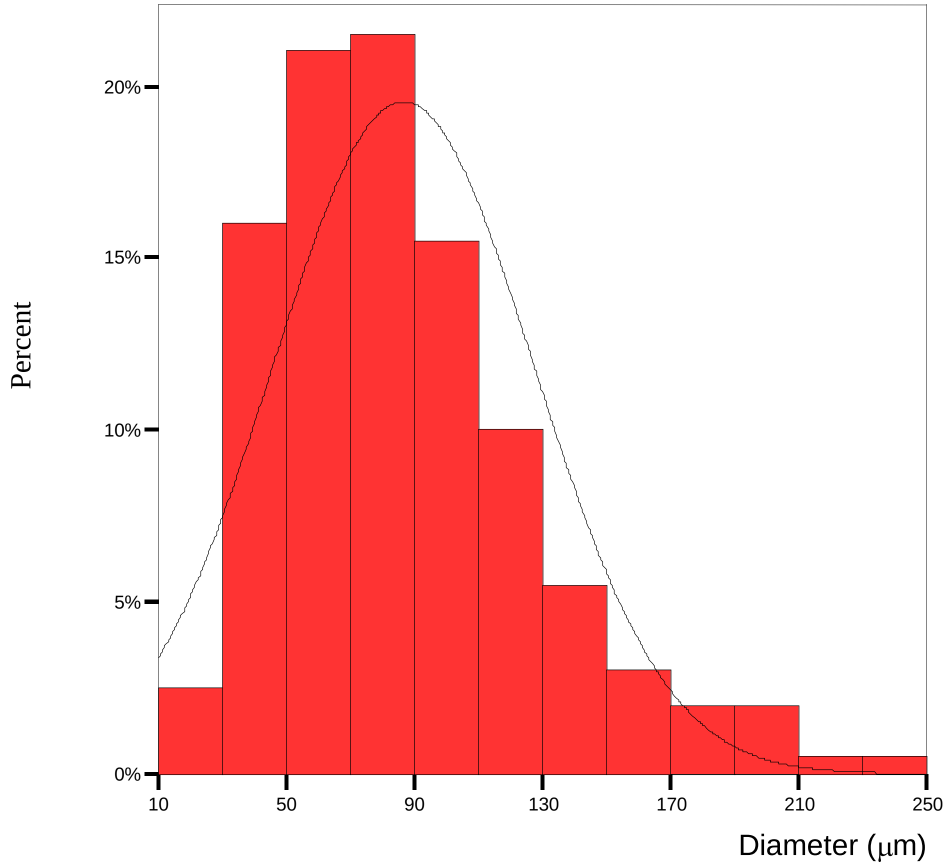

Table C-16 Flocs size distribution at PACl 60 mg/l with polymer 0.5 mg/l at 5°C

Mean		86.4
Std. Deviation		40.8
Kurtosis		1.2
Minimum		23.3
Maximum		236.8
Percentiles	5	33.9
	10	41.0
	30	60.0
	50	79.8
	80	116.7
	90	140.9
	95	175.6

Fig. C-17 Flocs size distribution at PACl 60mg/l with polymer 0.5mg/l and PAC 3mg/l at 5°C

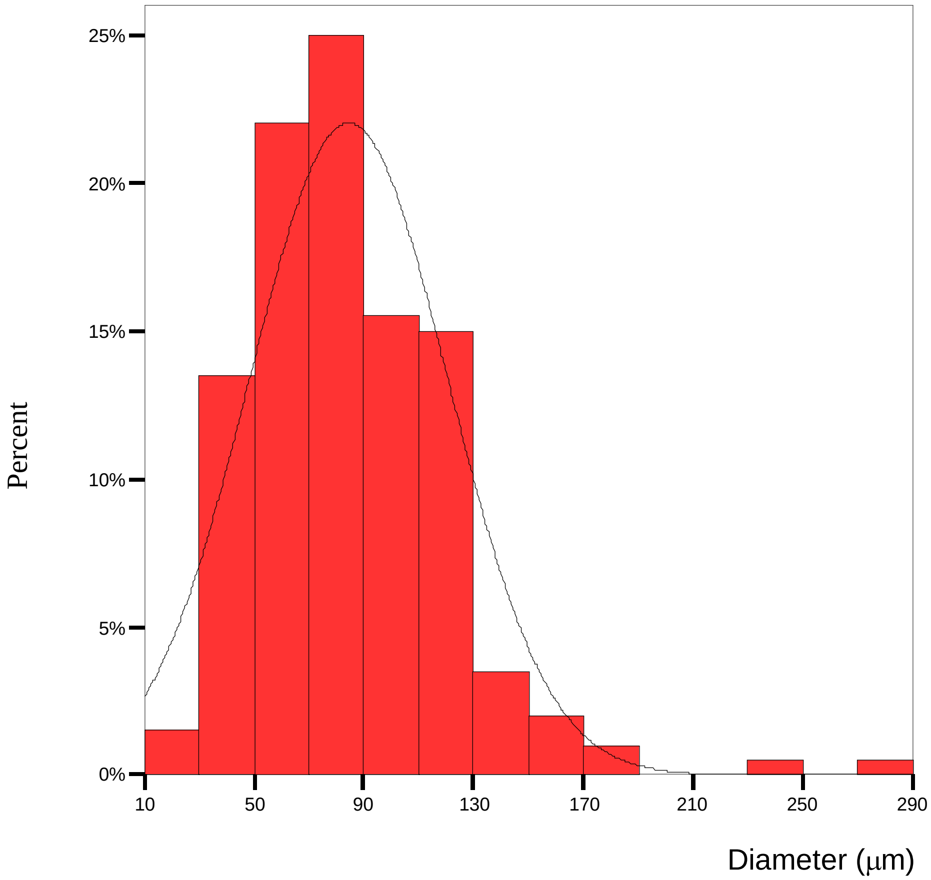

Table C-17 PACL60 with polymer0.5 and PAC3 FSD data at 5°C

Mean		92.4
Std. Deviation		36.2
Kurtosis		4.6
Minimum		25.2
Maximum		275.0
Percentiles	5	38.4
	10	45.5
	30	61.7
	50	80.1
	80	113.5
	90	126.0
	95	145.4

Fig. C-18 Flocs size distribution at alum 73 mg/l at 5°C

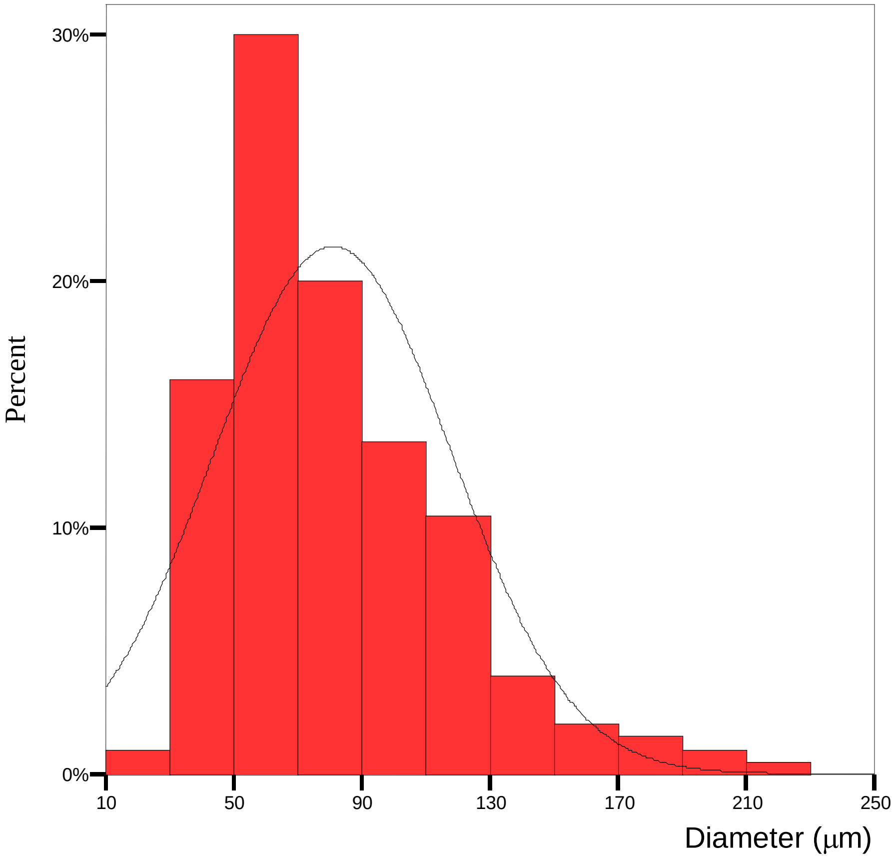

Table C-18 Flocs size distribution at alum 73 mg/l at 5°C

Mean		80.8
Std. Deviation		37.3
Kurtosis		1.3
Minimum		17.6
Maximum		220.2
Percentiles	5	34.3
	10	39.3
	30	56.3
	50	72.5
	80	109.0
	90	128.5
	95	156.1

Fig. C-19 Flocs size distribution at alum 73 mg/l with polymer 1.8 mg/l at 5°C

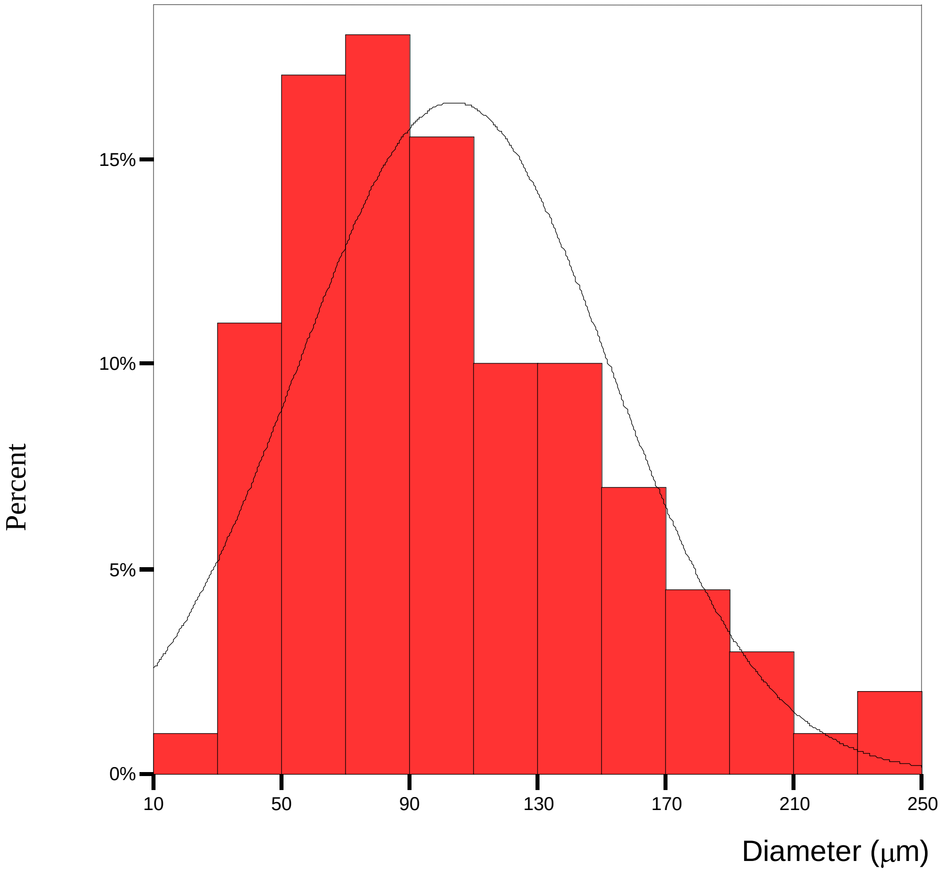

Table C-19 Flocs size distribution at alum 73 mg/l with polymer 1.8 mg/l at 5°C

Mean		103.6
Std. Deviation		48.8
Kurtosis		2.0
Minimum		21.9
Maximum		245.1
Percentiles	5	36.2
	10	45.5
	30	72.0
	50	94.5
	80	146.7
	90	174.7
	95	200.3

Fig. C-20 Flocs size distribution at alum 73 mg/l with polymer 1.8 mg/l and PAC 3 mg/l at 5°C

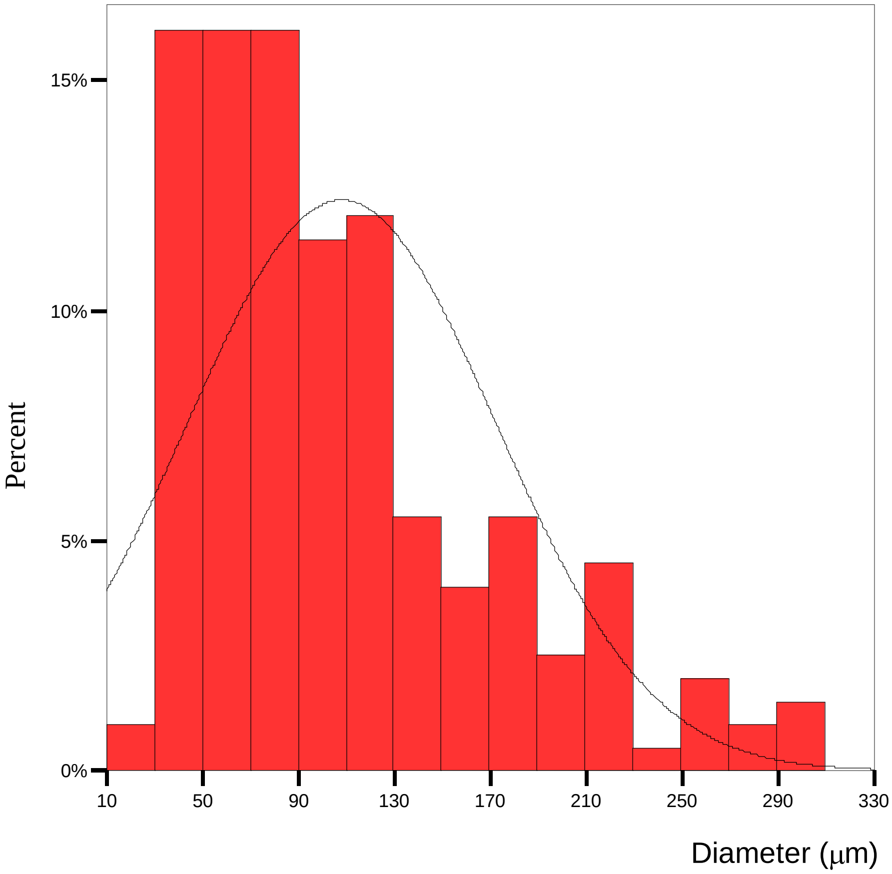

Table C-20 Flocs size distribution at alum 73 mg/l with polymer 1.8 mg/l and PAC 3 mg/l at 5°C

Mean		108.3
Std. Deviation		64.7
Kurtosis		1.8
Minimum		25.8
Maximum		330.3
Percentiles	5	34.9
	10	41.8
	30	62.6
	50	92.0
	80	160.0
	90	210.6
	95	250.8

Appendix D

Chemical Cost Estimates

1. Chemical prices (provided by Univar Canada Ltd.):

   PACl (Sternpac): \$0.96/kg; Alum: \$0.87/kg; Polymer (Superfloc C-591): \$2.88/kg

2. Transportation fee from Winnipeg to the Split Lake WTP: \$118/t

3. Optimum dosage:

   PACl: 84 mg/l; Alum: 100 mg/l; polymer: 0.5 mg/l

4. Water demand:

   Population: 2000; Per capita demand: 225 l/c/day

   Average daily flow = 2000×225 = 450 m^3/day

   Fire flow rate: 32 l/s; Fire flow duration: 1 hour; Fire frequent time: 1 time/year

   Fire water storage = $32 \times 60 \times 60$ =115.2 m^3

   Water losses coefficient: 10%

   Total water demand = 1.1 $\times (450 \times 365 + 115.2)$ = 180801 m^3/year

3. Cost estimates:

   - Cost of PACl = $0.96 \times 84 \times 10^{-6} \times 180801 \times 10^{3}$ = 0.96 x 15187 = \$14580/year
   - Cost of alum and polymer

     = 0.87 x 100 x 10^{-6} x 180801 x 10^3 + 2.88 x 0.5 x 10^{-6} x 180801 x 10^3

     = 0.87 x 18080 + 2.88 x 90.4 = \$15990/year

4. Chemical transportation fee from Winnipeg to Split Lake WTP

   - PACl = 118.44 x 15187/1000 = \$1799
   - Alum and polymer = 118.44 x (18080 + 90.4)/1000 = \$2152

5. Total saving = (15990 –14580 + 2152-1799)/(15990 + 2152) = 9.7 %

Appendix E

Photographs

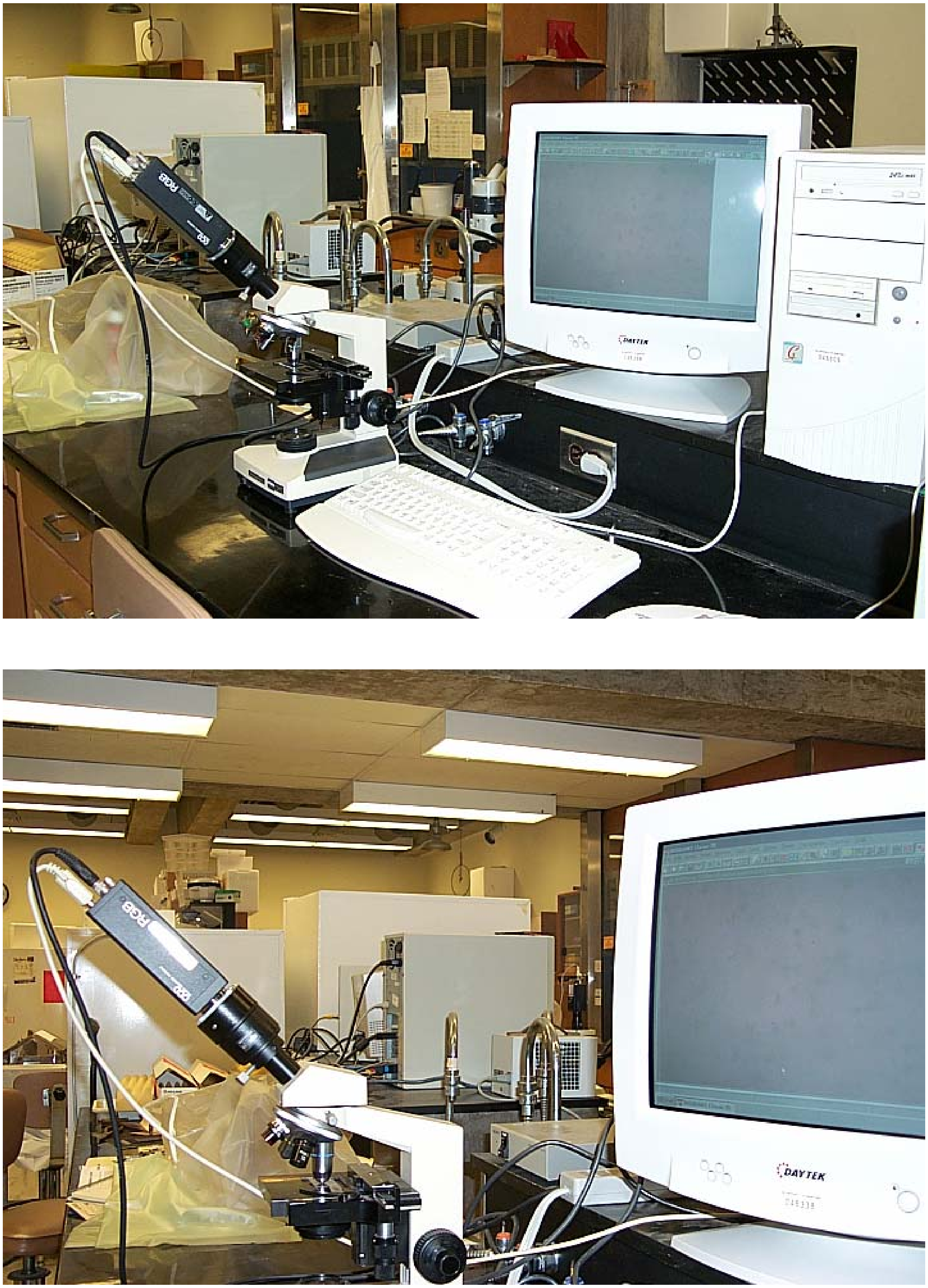

Figure E-1 Bioquant 95 image analysis equipment

Figure E-2 Coagulation jar tests at the Split Lake WTP

Figure E-3 Alum coagulant feeding facility at the Split Lake WTP