83-31-03

Technical Report

Chemical Conditioning of Municipal Wastewater Sludges Using Polyaluminum Chloride

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December 1985

December, 1985
Env. Eng. Report No. 89-85-6

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Submitted to the

Massachusetts Department of Environmental Quality Engineering
S. Russell Sylva, Commissioner
Division of Water Pollution Control
Thomas C. McMahon, Director

ACKNOWLEDGEMENT

This study was supported by Research and Demonstration Program funds from the Massachusetts Division of Water Pollution Control (MDWPC: Project Number 83-31). The authors are grateful to Arthur Screpetis of MDWPC for his assistance in having aluminum measurements made at the Lawrence Experiment Station as part of this project.

ABSTRACT

This study examined the feasibility of using polyaluminum chloride (PACl) as a chemical conditioner for municipal wastewater sludges. PACl is a low molecular weight inorganic cationic polymer of aluminum produced from the partial neutralization of an aluminum chloride solution. This study included a literature search, laboratory sludge dewatering experiments, and a cost evaluation. Sludge dewatering experiments were conducted to compare the effectiveness of PACl against alum, ferric chloride, Magnifloc 572C, and Aqualyte 104. The sludge used in the experiments was obtained from the Amherst Wastewater Treatment Facility. A Buchner funnel apparatus was used to measure sludge specific resistance and the time to collect 30 mL of filtrate. The latter measurement was used to evaluate any improvement in sludge dewatering rates from the addition of chemical conditioners. In addition, the total residual aluminum was measured in the filtrates of raw sludges, sludges conditioned with PACl, and sludges conditioned with alum.

The experimental results showed that PACl is a good chemical conditioning agent. It produced lower sludge dewatering times than alum by at least 50 percent. The sludge dewatering times at optimum dosages for PACl and ferric chloride were similar. PACl and the high molecular weight organic polyelectrolyte (Aqualyte 104) were more effective as chemical conditioners, giving lower sludge dewatering times, than the low molecular weight, high charge density cationic polyelectrolyte

(Magnifloc 572C). In addition, the total residual aluminum in the sludge treated with PACl was less than the total residual aluminum in the sludge treated with alum at their respective optimum dosages. The chemical cost evaluation of the chemical conditioners in relation to their optimum dosages in the laboratory sludge dewatering experiments showed that PACl is cheaper than alum and ferric chloride. However, this feasibility study was based on the Buchner funnel test and did not address the use of PACl in filter press dewatering equipment. Future research should examine the use of PACl on a pilot plant scale.

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$Al(OH)_3$ (s) -- solid form of aluminum hydroxide

$Al(OH)_3$(am) -- amorphous solid form of aluminum hydroxide

Al_T -- total aluminum

PACl -- polyaluminum chloride

CHAPTER I

INTRODUCTION

One of the areas of major concern in water and wastewater treatment is sludge handling and disposal. Sludge handling and disposal costs can account for 20 to 40 percent of the total operating and maintenance cost of a treatment facility (U.S. EPA (1976)). As an aid in the reduction of treatment costs, chemical conditioners have been used to alter sludge characteristics in order to increase the efficiency of sludge dewatering operations. Sludge dewatering operations facilitate the ultimate disposal of sludge by reducing the moisture content of the sludge.

In the chemical conditioning process, coagulant species increase particle size and facilitate solid-liquid separation of the sludge. O'Melia and Dempsey (1982) have indicated that alum is the most commonly used coagulant in the United States for the treatment of water supplies. As an alternative to alum, a partially hydrolysed aluminum chloride solution, generally called polyaluminum chloride (PACl), has been introduced in Japan and Europe (O'Melia and Dempsey (1982)). Although this low molecular weight cationic polymer is an unconventional coagulant in the United States, its application to water and wastewater treatment may increase substantially as the patents expire (Dempsey et al. (1985)).

The effectiveness of PACl as a coagulant has been proven through studies involving potable water treatment applications, particularly through its comparison with alum. Claims have been made that organic material in the presence of suspended solids is removed more easily with

PACl than with conventional coagulants of aluminum (Albert (1976), Fiessinger and Bersillon (1977)). In a study involving fulvic acid solutions, O'Melia and Dempsey (1982) indicated that the removal of fulvic acid occurred over a broader pH range with PACl (pH 3 to 7) than with alum (pH 4.5 to 6). Similarly, in an investigation by Dempsey *et al.* (1985) involving clay-fulvic acid suspensions, the critical coagulant concentration was lower at all pH values when PACl was used instead of alum. Although the difference between the effectiveness of PACl and alum was negligible at neutral pH, PACl was a more effective coagulant at higher or lower pH values.

In addition to the effectiveness of PACl in a broader pH range, the best settling PACl flocs had greater settling velocities than the best settling alum flocs within the experimental conditions used by Dempsey *et al.* (1985). Dempsey *et al.* also indicated that a decrease in sludge volume occurred since the required dose of PACl (as Al_T) was lower than alum (as Al_T). This decrease in sludge volume suggests that the use of PACl as a sludge conditioner could reduce the costs of sludge handling and disposal in water and wastewater treatment.

The primary objective of the research was to evaluate the feasibility of using PACl as a chemical conditioner for municipal wastewater sludges. The specific goals of the study included the following:

1. To review the literature regarding the use of PACl in water and wastewater treatment;

2. To conduct laboratory sludge dewatering experiments comparing the effectiveness of PACl against alum, ferric chloride, Magnifloc 572C (low molecular weight, high positive charge density polymer) and Aqualyte 104 (high molecular weight, cationic polymer);
3. To compare total aluminum residuals in the filtrates of raw sludges, sludges conditioned with PACl, and sludges conditioned with alum; and
4. To evaluate the cost of using PACl as a chemical conditioner.

CHAPTER II

LITERATURE REVIEW

In the initial stage of this study, a computer aided literature search was conducted through DIALOG Information Services, Incorporated. The data bases for this literature search included Water Net, Chem Abstracts, and Pollution Abstracts. This chapter provides background information from the literature search through a discussion of the effects of aluminum species on coagulation, a description of polyaluminum chloride (PACl) and its preparation, and a review of the effects of sludge properties on dewatering.

Effects of Aluminum Species on Coagulation

Dempsey et al. (1985) suggest that the active coagulant species in PACl and alum are the polymers and precipitates of aluminum. The ability of aluminum to function as a coagulant is discussed through a review of the aqueous chemistry of aluminum and mechanisms of coagulation.

Aqueous Chemistry of Aluminum

O'Melia and Dempsey (1982) have explained aluminum coagulation through a discussion of the aqueous chemistry of aluminum. The addition of aluminum to water results in the formation of soluble monomeric species, polymeric species, and solid precipitates. Dempsey, Ganho, and

O'Melia (1984) have indicated that the simplest polymer is $Al_2(OH)_2^{4+}$. As the polymer grows, hexameric rings form and condense to create a two-dimensional sheet. Hydrogen bonding and van der Waals forces bind the sheets together, eventually causing them to form three-dimensional amorphous $Al(OH)_3$(am). Polymeric species tend to predominate at pH levels below 6 with solid $Al(OH)_3$(am) precipitating at pH levels above 6. Among the polymeric species, Parthasarathy and Buffle (1985) concluded that the $Al_{13}O_4(OH)_{24}^{7+}$ species is the smallest stable undissociable polymer.

As O'Melia and Dempsey (1982) have indicated, one cause of uncertainty in evaluating aluminum species in water is the formation of crystalline $Al(OH)_3$(s) from $Al(OH)_3$(am) that occurs over an extended period of time. Fresh precipitates can be amorphous and more soluble than crystalline forms. Thus, the concentration of polymeric aluminum species such as $Al_{13}O_4(OH)_{24}^{7+}$ that can exist in water at equilibrium with the crystalline solid gibbsite alpha-$Al(OH)_3$(s) is several orders of magnitude lower in aluminum, than when $Al(OH)_3$(am) is considered as the solid phase. This difference affects aluminum speciation in terms of its behavior as a coagulant and affects the preparation of stable stock solutions of polymeric aluminum species, e.g. polyaluminum chloride.

As O'Melia and Dempsey (1982) have indicated, the addition of base to aluminum solutions in the presence of chloride or nitrate ions can produce monomers and polymers that are stable for months or years. In their study, $Al(OH)_3$(s) did not precipitate until the ratio of [OH] to [Al] exceeded 2.4 at pH levels of about 6. In general, stable aluminum species in the presence of chloride or nitrate ions had a tendency to form at pH levels below 6 with $Al(OH)_3(s)$ forming at pH levels above 6. PACl which is produced from the partial neutralization of $AlCl_3$ exhibits this property.

In addition, O'Melia and Dempsey (1982) also studied the effects of adding base to aluminum sulfate solutions. In contrast to the aluminum chloride solutions, $Al(OH)_3(s)$ precipitated at [OH] to [Al] ratios of only 0.5 with pH levels of about 4. $Al(OH)_3(s)$ is generally formed when hydroxide ions and van der Waals interactions link polymers together. In aluminum chloride solutions, the highly positively charged polynuclear hydroxoaluminum complexes prevent this nucleation; however, the presence of sulfate catalyzes the formation of the precipitate. Sulfate ions form weak complexes with aluminum, but screen the positive charges of the aluminum cations and catalyze their growth into a solid lattice. Most coagulation experiments have used a form of PACl that did not contain sulfate (Dempsey, Ganho, and O'Melia (1984), Dempsey et al. (1985), O'Melia and Dempsey (1982), Parthasarathy and Buffle (1985)).

Coagulation Mechanisms

Stumm and O'Melia (1968) have discussed two possible ways in which aluminum functions as a coagulant for the removal of turbidity. In the first process, positively charged aluminum polymers are attracted to negatively charged particles. The charge neutralization of the turbidity-causing particles results in effective aggregation when sufficient contact opportunities are present. Thus, this process is most applicable to concentrated suspensions in which flocculation is rapid, and at pH levels where cationic aluminum polymers are readily formed (pH 5 to 6).

In the second mechanism discussed by Stumm and O'Melia (1968), coagulation involves the precipitation of $Al(OH)_3(s)$. The negatively charged colloids are enmeshed in this precipitate as it forms. This process is termed "sweep floc." In contrast to the charge neutralization mechanism, "sweep floc" is effective in treating low turbidity waters. The solid precipitate produced increases contact opportunities in the low turbidity waters, thus increasing the rate of flocculation.

Similarly, O'Melia and Dempsey (1982) have also discussed the removal of organic matter through charge neutralization and adsorption. Their study focused on the coagulation of organic matter using alum and PACl. In the first case involving alum, coagulation occurred through charge neutralization at pH levels less than 5. At pH levels between 5 and 6, the dominant mechanism was dependent on the applied dosage of aluminum. At low aluminum dosages, charge neutralization of the organic matter can occur. At pH levels above 7, removal of organic matter occurred through adsorption on precipitates of $Al(OH)_3(s)$. However, in the case involving PACl, charge neutralization was the dominant mechanism for coagulation within the pH range of 3 to 7.

Polyaluminum Chloride

Description and Preparation

Parthasarathy and Buffle (1985) conducted a study on the properties of polyaluminum chloride (PACl) and the optimum conditions for its preparation. This low molecular weight cationic polymer is prepared by the slow addition of a base ($NaHCO_3$, Na_2CO_3, NaOH, or $Ca(OH)_2$) to an aluminum salt solution. Farrington (1983) represents PACl as

$$Al_n(OH)_mCl_{3n-m}$$

where n and m are integers. The solution may also contain sulfate as represented by Grayson et al. (1984)

$$Al(OH)_{1.5}(SO_4)_{0.125}Cl_{1.25}$$

The partial neutralization of an aluminum salt to form PACl produces various types of Al(III) species. On the basis of their rates of reaction with ferron or 8-hydroxyquinoline, Parthasarathy and Buffle have classified these species into three categories: fast reacting monomeric species, slow reacting metastable polymeric species, and very slow reacting species consisting of fine precipitates of $Al(OH)_3(s)$. The proportions of these species are dependent on factors such as ionic strength, Al(III) concentrations, rate of addition of base, hydroxide to aluminum ratio, temperature, and aging.

Parthasarathy and Buffle (1985) determined that the optimum conditions for the preparation of PACl occur when the average net charge per aluminum atom is maximum; i.e., when the degree of hydrolysis is low, but sufficient to form a stable polymer that will not readily precipitate. Results from their experiments suggest that polymeric aluminum(III) hydroxide species have an average residual positive charge per mole of aluminum of 0.54. This implies that highly positive charged species are formed in solution that should theoretically make PACl an effective coagulant. In addition, Parthasarathy and Buffle suggest that the polymeric aluminum(III) hydroxide species has a size between 10 and 20 Å and that the species constitutes approximately 80 percent of the total aluminum in the hydrolyzed solution. The formation of stable, small size polymers with maximum yield are obtained when the [OH] to [Al] ratio is greater than 2.5 and less than 2.9. These polymers do not degrade to a great extent by either dilution or variation of pH over the pH range from 4 to 6.5. Although one or more species are formed in solution, Parthasarathy and Buffle concluded that $Al_{13}O_4(OH)_{24}^{7+}$ species is the smallest stable undissociable polymer. In regards to dilution effects, Parthasarathy and Buffle also state that the composition of the solution remained unaffected for at least 3 days.

Parthasarathy and Buffle also found that the pH and the distribution of the species are affected by aging. The pH of PACl decreases with time. When the base is added slowly, the extent of the decline in pH is smaller. Slow neutralization probably leads to the production of more stable polymers. The distribution of these Al(III) species is dependent on the [OH] to [Al] ratio and the total Al concentration, and is affected by time. In general, the amount of $Al(OH)_3(s)$ tends to increase with time while the slow reacting metastable polymeric species decrease with time. However, these metastable species are considered to be stable over a long period of time provided that the [OH] to [Al] ratio is 2.5 , a high total aluminum concentration is used, and the mode of preparation produces a minimum amount of fine precipitates of $Al(OH)_3$ (s).

Coagulation Using Polyaluminum Chloride

Although the literature search showed no indication of any previous use of PACl in wastewater treatment applications, PACl has been used as a coagulant in potable water treatment. O'Melia and Dempsey (1982) investigated the precipitation of fulvic acid by aluminum polymers. In both cases involving PACl and alum, $Al(OH)_3$(s) was precipitated at neutral pH and fulvic acid was removed by first adsorbing on the $Al(OH)_3$(s) precipitate followed by settling of the floc. The pH region in which this occurred was narrower with PACl than with alum. The sulfate ions with alum catalyze the precipitation of $Al(OH)_3$(s). However, precipitation of fulvic acid by Al polymers occurred over a broader pH range with PACl (pH 3 to 7) than with alum (pH 4.5 to 6). This advantage over alum is attributed to the fact that the cationic polymers active in the coagulation process are preformed with PACl, whereas the polymers must be formed in the water being treated when alum is used.

Effects of Sludge Properties on Dewatering

In order to maximize the efficiency of sludge dewatering operations through sludge conditioning, the proper chemical conditioner must be selected and its optimum dosage must be determined. The effectiveness of the chemical conditioner is dependent on the characteristics of the sludge. Tiravanti, Lore, and Sonnante (1985) indicated that variations occurred in their laboratory dewatering investigations between samples of the same sludge type taken from a specific sewage plant at different times. Thus, a discussion of the effects of general sludge properties on dewaterability is beneficial to this study.

Specific Resistance

One method of quantitatively measuring sludge dewaterability is through specific resistance. Specific resistance measurements are useful in evaluating parameters that affect dewatering. Karr and Keinath (1978) define specific resistance as a measure of the resistance offered by a sludge to the withdrawal of water. Sludges with higher specific resistances are more difficult to dewater.

Specific resistance determinations are usually made through Buchner funnel tests. Karr and Keinath (1978) briefly outline this test. To conduct the specific resistance test, a known volume of sludge is poured into a Buchner funnel containing a premoistened filter paper. A vacuum is then applied. The rate of filtration is determined by measuring the volume of filtrate (V) collected at known increments of time (t). A graph of t/V versus V is plotted from the experimental results. The slope b of a straight line drawn through the data points is determined. This value is substituted into the specific resistance equation developed by Carman (Coackley and Jones (1956)):

$$r = \frac{2\,b\,P\,A^2}{\mu\,C} \qquad (1)$$

where r = specific resistance, m/kg

b = slope from graph of t/V versus V, sec/m^6

P = pressure applied across the cake, N/m^2

A = area of the filter paper, m^2

μ = viscosity of the filtrate, N-sec/m^2

C = weight of dry suspended solids in the cake per unit volume of filtrate, kg/m^3

Sludge Characteristics

Particle Size. A primary objective of sludge conditioning is to increase particle size by combining the small particles into larger aggregates (U.S. EPA (1979)). Particle size is a major factor that influences the dewaterability of sludge. Knocke and Wakeland (1983) concluded that particle size variations affect dewatering rates by changing the specific surface area associated with the sludge. Large particles have less surface area per unit weight of solids. Thus, increasing particle size improves dewatering rates.

In addition to individual particle sizes, Karr and Keinath (1978) conducted studies on particle size distribution. Their work indicated that similar specific resistances resulted regardless of sludge type, used when the particle size distributions were matched.

Compressibility. Since sludge particles are compressible, variations in the applied pressure differential P in Equation (1) affects specific resistance (Knocke and Wakeland (1983)). An increase in compressibility results in a decrease in specific resistance. Wakeland (1982) further suggested that floc density may have an impact on sludge compressibility. Particles of greater density tend to have lower compressibility coefficients.

Floc Strength. The floc strength of sludge is a major influencing factor on the operational system of sludge dewatering. Floc strength is mainly affected by mixing conditions. Results from studies conducted by Wakeland (1982) indicated that polymer conditioning improved sludge dewatering rates under conditions of low mixing intensities. Under intense mixing conditions, however, floc rupture resulted which decreased the effectiveness of the sludge conditioners. Floc rupture may also cause the release of fine particles capable of migrating through the sludge cake and blinding the filter media. Thus sludge conditioners should be added under conditions that promote the production of large stable flocs that can withstand the shear forces of sludge dewatering equipment.

pH. Roberts and Olsson (1975) suggested that the main factor in dewaterability is the reaction between positively charged polymers and the negatively charged particles of the sludge. In an investigation conducted by Karr and Keinath (1978), the dewaterability of activated sludge improved as pH decreased. The primary charge of the colloidal particles is reduced with pH, thereby promoting aggregation.

Polymer selection and dose requirements are also dependent on the sludge pH. Novak and O'Brien (1975) suggested that cationic polymers function effectively for sludge conditioning in the neutral and slightly acidic range. At higher pH levels, Novak and O'Brien suggested the use of high-activity anionic polymers.

CHAPTER III

EXPERIMENTAL MATERIALS AND METHODS

Chemical Conditioners

The feasibility of using polyaluminum chloride (PACl) as a chemical conditioner for municipal wastewater sludges was studied by comparing its effectiveness against other commonly used chemical conditioners. Table 1 lists the chemicals used in these experiments with some of their general properties. Alum and ferric chloride were used to represent inorganic chemicals. Aqualyte 104 and Magnifloc 572C represented high molecular weight and low molecular weight cationic polyelectrolytes, respectively. Aqualyte 104 is the chemical conditioner used at the Amherst Wastewater Treatment Facility.

Two types of PACl were supplied by PPG Industries, Pittsburgh, Pennsylvania. The supplier provided information indicating that the PACl sample containing sulfate had an aluminum concentration of 10 percent as Al_2O_3 (or 2.0 M Al_T), while the PACl without sulfate was 18 percent Al_2O_3 (3.5 M Al_T) (Weber (1985)). However, measurements conducted at the University of Massachusetts indicated that the total aluminum content of the PACl without sulfate was higher at 24 percent Al_2O_3 (4.76 M Al_T) (Ryan (1985)). This measured concentration was used to determine the chemical dosages for the PACl product without sulfate.

Ferric chloride is the most commonly used chemical conditioner in the United States (U.S. EPA (1979)). Since the dewatering properties of

Table 1

CHEMICAL CONDITIONERS

CHEMICAL	SUPPLIER	GENERAL PROPERTIES
Alum $Al_2(SO_4)_3$ 18 H_2O	Fisher Scientific, Co.	Inorganic chemical
Aqualyte 104	Tannin Corporation	Organic cationic polyelectrolyte High molecular weight
Ferric Chloride $FeCl_3 \cdot 6\ H_2O$	Fisher Scientific, Co.	Inorganic chemical Polyvalent metal salt
Magnifloc 572C	American Cyanamid, Co. Wayne, N.J.	Organic cationic polyelectrolyte High charge density Low molecular weight
Polyaluminum Chloride PACl	PPG Industries, Inc. Pittsburgh, Penn.	Low molecular weight Cationic polymer PACl: 24% Al_2O_3 PACl (w/SO_4): 10% Al_2O_3

municipal wastewater sludges may vary on a daily basis, ferric chloride was used in each set of experiments for comparative purposes. Stock solutions of Magnifloc 572C (5 g/L), $FeCl_3$ (10 g/L), PACl (12.85 g/L Al_T and 1.29 g/L Al_T), and PACl with sulfate (5.3 g/L Al_T and 0.53 g/L Al_T) were prepared within one hour of experimentation.

Sludge Sampling

The sludge used in the experiments was obtained from the Amherst Wastewater Treatment Facility. In this facility, waste activated sludge is chemically conditioned with Aqualyte 104 (a high molecular weight cationic polyelectrolyte) during the dissolved air flotation thickening process. This thickened sludge is then combined with primary sludge prior to vacuum filtration (Pariseau (1985)).

For the purposes of this study, a volumetric ratio of 7 parts primary sludge to 4 parts waste activated sludge was used in the sludge conditioning experiments. Samples were collected at the Amherst plant prior to conditioning of the waste activated sludge. Since pure activated sludge is subject to high variability, a higher concentration of primary sludge was selected in relation to waste activated sludge (Novak (1984)). The sludge samples were collected and mixed in a 20 liter plastic carboy. The resulting suspended solids content of the raw sludge ranged from 1 to 3 percent. In order to minimize changes in sludge properties that may result from biological activity, all experiments were completed within 8 hours of sample collection.

In this research, 7 sets of experiments were conducted. A description of each is given in Table 2. Ferric chloride was used in all experiments. Set number 7 was used to investigate the effects of varying the ratios of primary sludge to waste activated sludge on the optimum dosage of ferric chloride. In the other 6 sets of experiments, the sludge was conditioned with the organic and inorganic chemicals listed in Table 1. Each set involved three chemicals, one of which was ferric chloride.

Laboratory Methods

The sludge conditioning results presented in this report were obtained from 7 sets of experiments in which a series of 500 mL sludge samples were conditioned with the various chemicals listed in Table 1 under controlled mixing conditions. Sludge samples were treated with the chemical conditioner being tested at a rapid mixing speed of 100 rpm for one minute. The sludge was then slowly mixed for 5 minutes at a rate of 20 rpm. After the mixer was turned off, an aliquot of conditioned sludge was placed in a 10 cm Buchner funnel containing a premoistened Whatman #1 filter paper. Under an applied vacuum of 15 in Hg ($50.7 \times 10^3 N/m^2$), the time to collect 30 mL of filtrate was determined. The time of filtration for a specific volume of filtrate is a rapid measure of sludge dewaterability (Novak (1979)). The laboratory apparatus for this sludge dewatering procedure is shown in Figure 1.

Table 2

DESCRIPTION OF SLUDGE DEWATERING EXPERIMENTS

SET NUMBER	DESCRIPTION
1	Effects of ferric chloride, alum, and PACl
2	Effects of ferric chloride, Aqualyte 104, and Magnifloc 572C
3	Effects of ferric chloride, alum, and PACl
4	Effects of ferric chloride, Aqualyte 104, and Magnifloc 572C
5	Effects of ferric chloride, alum, and PACl (with SO_4)
6	Effects of ferric chloride, alum, and PACl (with SO_4)
7	Effects of various ratios of primary sludge to waste activated sludge on optimal dosage of ferric chloride

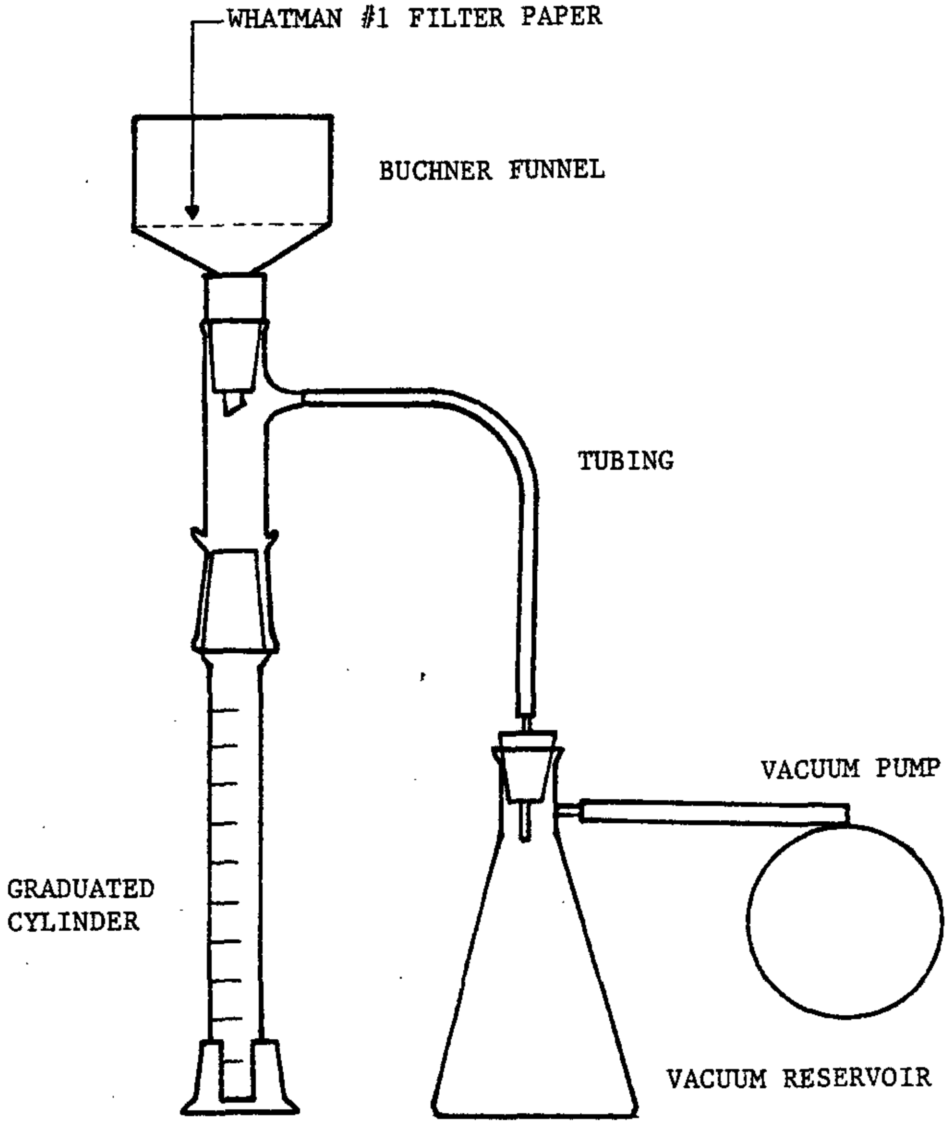

Figure 1. Laboratory Apparatus for Sludge Dewatering

The final pH and temperature of the conditioned samples were also measured.

In each set of experiments, the unconditioned raw sludge served as a control. The pH, temperature, and time to dewater 30 mL of filtrate of the raw sludge were determined. In addition, the sludge was characterized for suspended solids content and total solids content according to Standard Methods (APHA, AWWA, and WPCF (1985)). The dry weight of the filter cake solids was used to indicate the total solids content of the sludge. The specific resistance of the sludge was calculated according to Carman's theory as described by Coackley and Jones (1956).

Residual Aluminum

In the experiments involving PACl and alum, residual aluminum measurements were made on the filtrate of the dewatered sludges and on the raw untreated sludge. The samples were acidified with nitric acid as a preservative and refrigerated prior to the measurements. Aluminum measurements were provided by the University of Massachusetts Microanalysis Laboratory in Amherst and the Lawrence Experiment Station in Lawrence, Massachusetts. The laboratories used the emission spectroscopy (with an inductively coupled plasma source) and the atomic absorption spectrometry, respectively.

CHAPTER IV

RESULTS AND ANALYSIS

Sludge Dewatering Experiments

Effects of Chemical Conditioners

The results of the sludge dewatering experiments are presented using graphs in which the time to dewater 30 mL of filtrate is plotted as a function of chemical dosage.

The sludge dewatering results of ferric chloride, alum, and polyaluminum chloride (PACl) are shown in Figures 2 and 3. In Figure 2, the raw sludge had a suspended solids content of 0.78 percent and a specific resistance of 1.03×10^{12} m/kg . The effects of adding ferric chloride and PACl on this sludge were similar. Both ferric chloride and PACl produced lower sludge dewatering times by approximately 50 percent than did alum. Figure 2.B shows a sludge dewatering time of about 55 seconds at an optimum alum dosage of 300 mg/L while Figure 2.C shows a sludge dewatering time of about 30 seconds for an optimum PACl dosage of 77 mg/L as Al_T. As shown in Figure 2.B, alum also restabilized the sludge, producing longer dewatering times at dosages above the optimum dosage.

A set of experiments involving ferric chloride, alum, and PACl was repeated on a raw sludge with a suspended solids content of 2.64 percent and a specific resistance of 1.20×10^{12} m/kg . The results from this set are shown in Figure 3 and are analogous to the previous results.

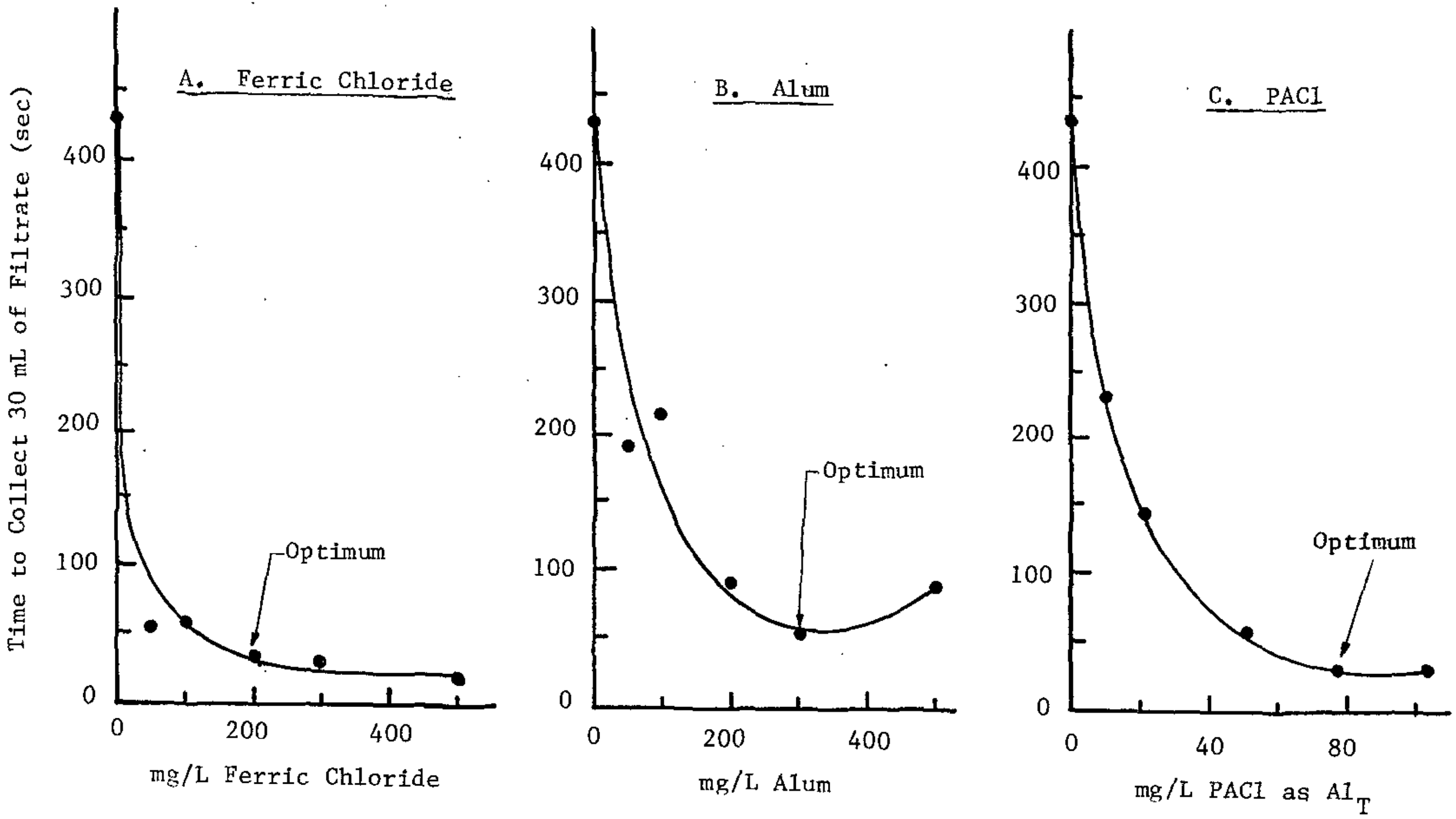

Figure 2. Time to Collect 30 mL of Filtrate vs. Chemical Dosage (Sludge Dewatering Exp. #1; Raw Sludge Characteristics: Suspended Solids = 0.78%, Specific Resistance = 1.03×10^{12} m/kg)

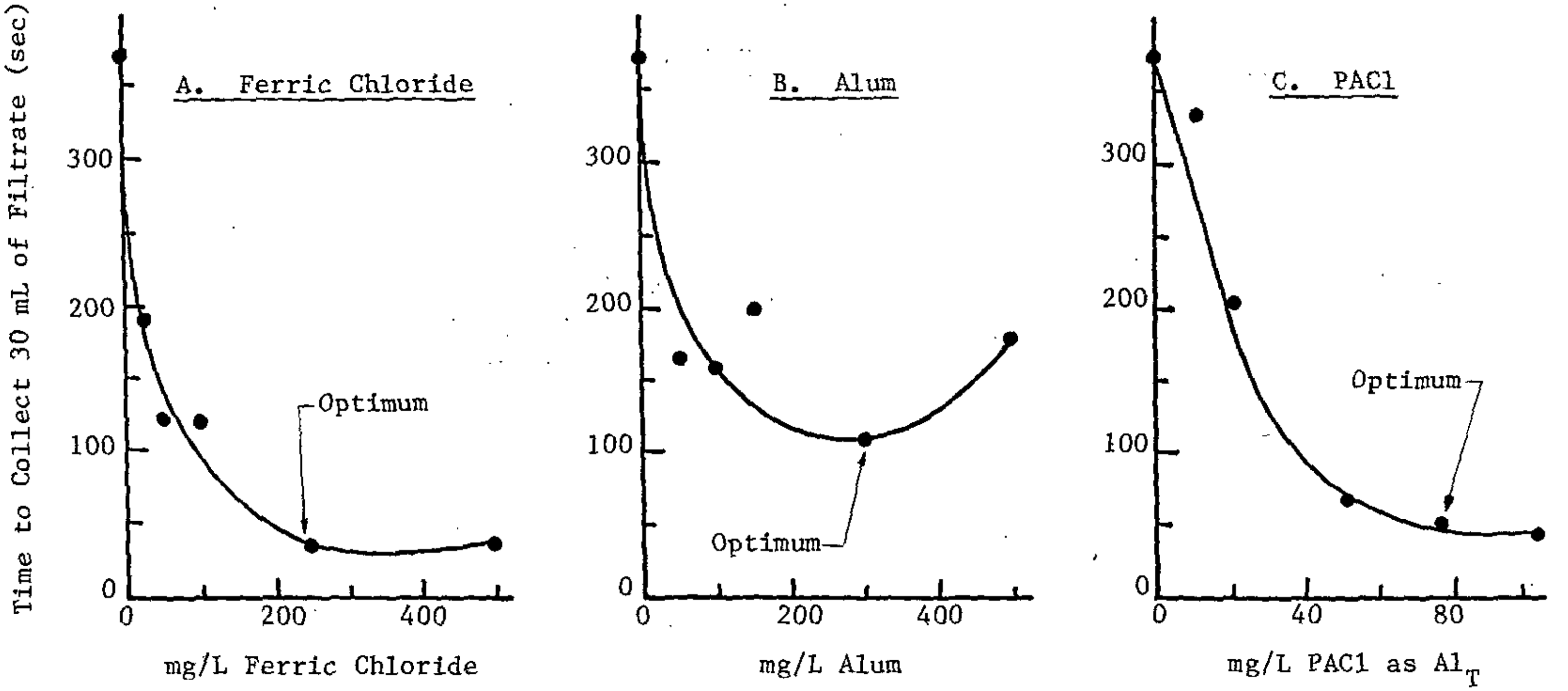

Figure 3. Time to Collect 30 mL of Filtrate vs. Chemical Dosage (Sludge Dewatering Exp. #3; Raw Sludge Characteristics: Suspended Solids = 2.64%, Specific Resistance = 1.20×10^{12} m/kg)

Both PACl and ferric chloride provided sludge dewatering times of at least 50 percent less than alum. However, sludge dewatering times for both PACl and alum in Figure 3 are almost twice as long as the dewatering times for the experiments shown in Figure 2. The difference between these sludge dewatering times may be attributed to the increase in suspended solids content of the raw sludge from 0.78 percent in Figure 2 to 2.64 percent in Figure 3. However, the increase in suspended solids content and specific resistance did not have a major effect on the sludge dewatering time of ferric chloride or on the required dosages for any of the conditioners i.e., ferric chloride, alum, and PACl. Optimum chemical dosages for alum and PACl in Figure 3 are equivalent to their optimum chemical dosages in Figure 2, while the ferric chloride dosage increased slightly from 200 to 250 mg/L. The effect of specific resistance on the required dosage of the other chemical conditioners will be addressed later.

In addition to the experiments involving PACl, two sets of experiments were also conducted using another PACl product that contains some sulfate (refer to Table 1). The results of these experiments are shown in Figures 4 and 5. In Figure 4, the raw sludge treated had a suspended solids content of 2.20 percent with a specific resistance of 3.30×10^{12} m/kg . In Figure 5, the raw sludge had a suspended solids content of 2.50 percent and a specific resistance of 4.40×10^{12} m/kg. In comparison to the PACl without sulfate, PACl with sulfate also resulted in a lower sludge dewatering time than alum by at least 50 percent in both sets of experiments. Although specific resistance had no effect on the

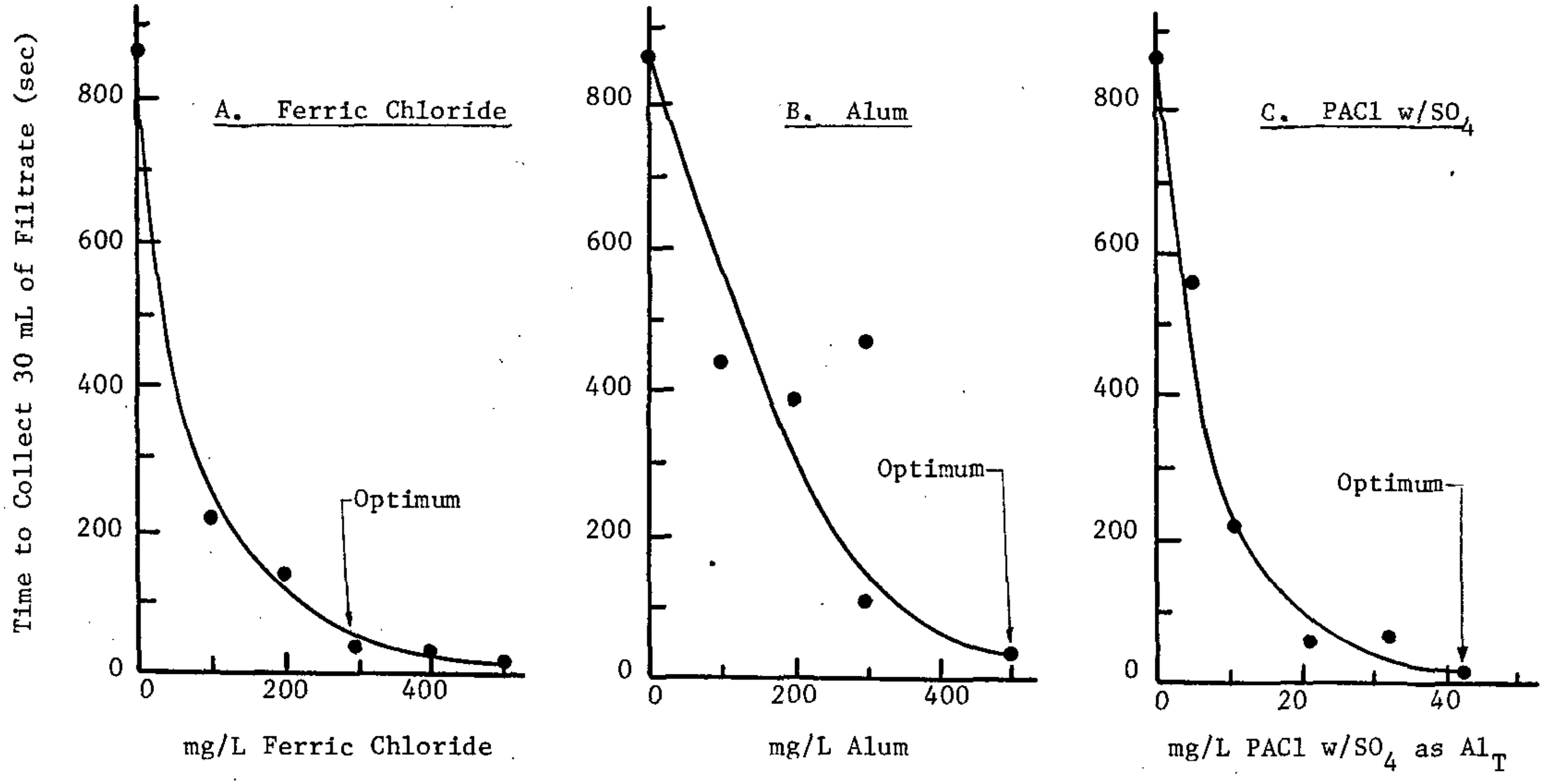

Figure 4. Time to Collect 30 mL of Filtrate vs. Chemical Dosage (Sludge Dewatering Exp. #5; Raw Sludge Characteristics: Suspended Solids = 2.20%, Specific Resistance = 3.30×10^{12} m/kg)

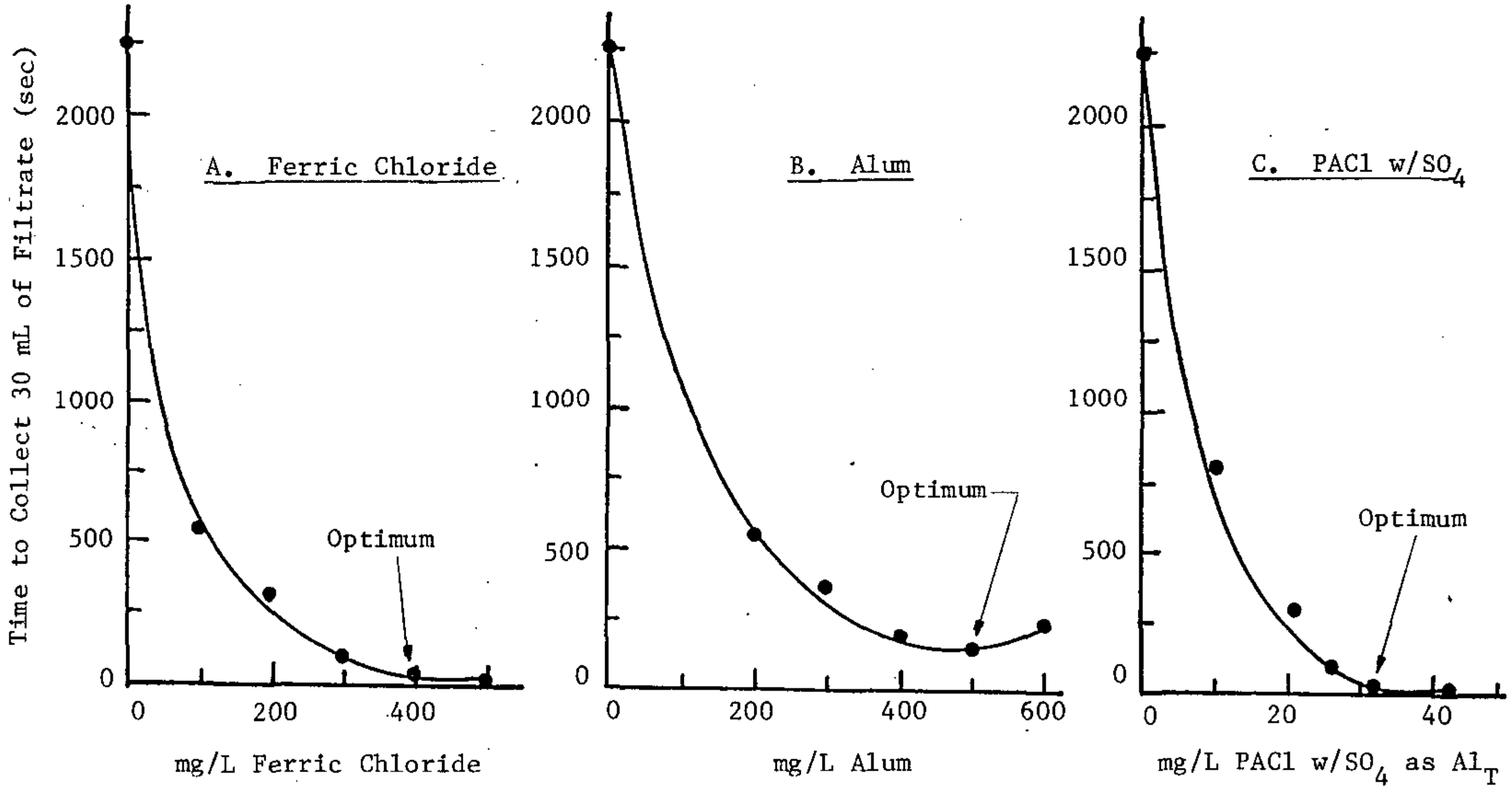

Figure 5. Time to Collect 30 mL of Filtrate vs. Chemical Dosage (Sludge Dewatering Exp. #6; Raw Sludge Characteristics: Suspended Solids = 2.50%, Specific Resistance = 4.40×10^{12} m/kg)

chemical dosages of the previous experiments involving PACl without sulfate, variations occurred in the experiments involving PACl with sulfate. The increase in raw sludge specific resistance resulted in an increase in ferric chloride dosage from 300 to 400 mg/L and a decrease in the PACl (with sulfate) dosage from 42 to 32 mg/L Al_T. However, the increase in specific resistance had no effect on the alum dosage.

In this study, the effects of organic chemical conditioners (Magnifloc 572C and Aqualyte 104) on sludge dewatering were also evaluated and compared to ferric chloride. The results of these experiments are presented in Figures 6 and 7. In Figure 6, the raw sludge treated had a suspended solids content of 1.98 percent and a specific resistance of 6.91×10^{11} m/kg . Aqualyte 104, the high molecular weight cationic polyelectrolyte used at the Amherst Wastewater Treatment Facility, provided the most efficient sludge dewatering results. The sludge dewatering time for Aqualyte 104 was more than 75 percent less than the dewatering time of ferric chloride and 83 percent less than that for Magnifloc 572C. The results shown in Figure 7 are analogous to the results shown in Figure 6. In both sets of experiments, Aqualyte 104 produced the lowest sludge dewatering time followed by ferric chloride and Magnifloc 572C, respectively. In Figure 7, the raw sludge had a suspended solids content of 2.10 percent with a specific resistance of 2.20×10^{12} m/kg . The increase in specific resistance resulted in an increase in the ferric chloride dosage from 300 to 400 mg/L and an increase in the Magnifloc 572C dosage from 75 to 200 mg/L. However, the increase in specific resistance resulted in a decrease in

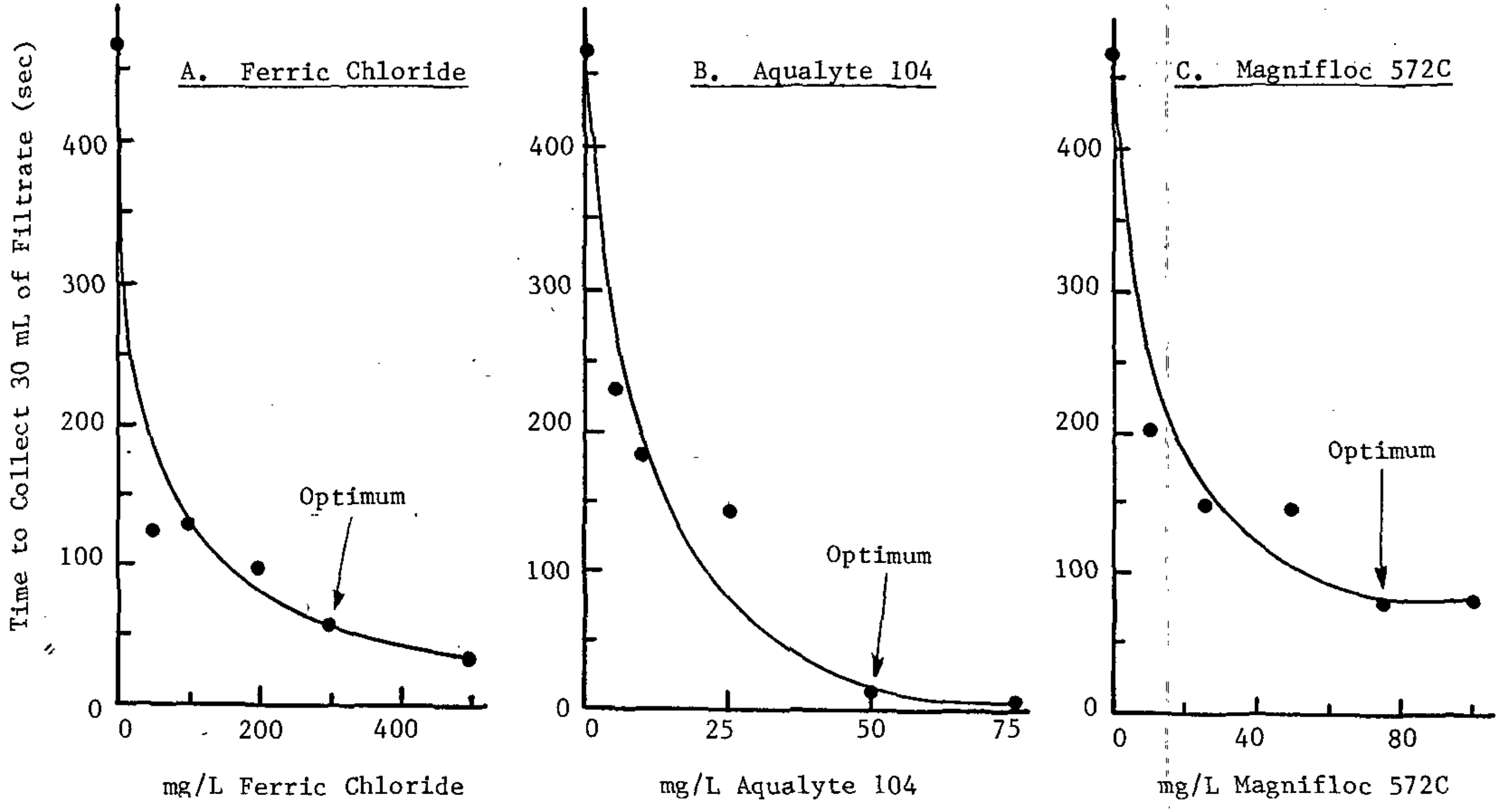

Figure 6. Time to Collect 30 mL of Filtrate vs. Chemical Dosage (Sludge Dewatering Exp. #2; Raw Sludge Characteristics: Suspended Solids = 1.98%, Specific Resistance = 6.91×10^{11} m/kg)

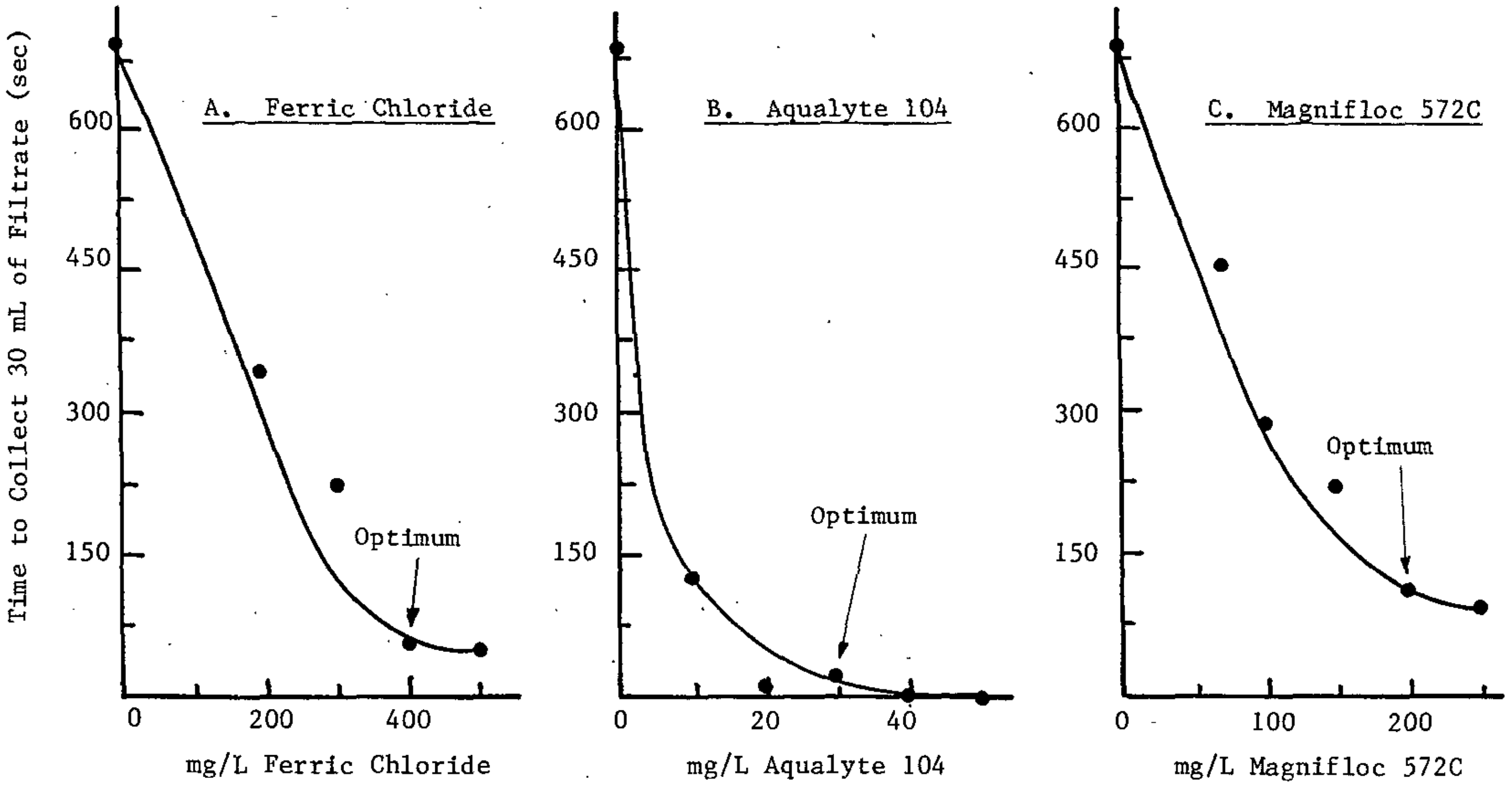

Figure 7. Time to Collect 30 mL of Filtrate vs. Chemical Dosage (Sludge Dewatering Exp. #4; Raw Sludge Characteristics: Suspended Solids = 2.10%, Specific Resistance = 2.20×10^{12} m/kg)

the Aqualyte 104 dosage from 50 to 30 mg/L. No specific explanation can be given for the large increase in the Magnifloc 572C dosage.

Raw sludge data, optimum chemical dosages, and sludge dewatering times are summarized in Tables 3 and 4, respectively. The maximum variation between the initial pH of the raw sludges and the final pH of all conditioned sludges was 0.6. In general, the pH of the sludge decreased with increasing dosage of all the chemical conditioners used.

In summary, the experiments indicated that both ferric chloride and PACl (with and without sulfate) produced lower sludge dewatering times than alum by at least 50 percent. Thus in cases where alum is used as a chemical conditioner, PACl may be used as a substitute. In both experiments involving ferric chloride, Aqualyte 104, and Magnifloc 572C, Aqualyte 104 produced the lowest sludge dewatering time. In general, PACl and Aqualyte 104 gave lower sludge dewatering times than the low molecular weight, high charge density polyelectroyte (Magnifloc 572C).

The effect of specific resistance on the optimum dosage of each chemical conditioner varied. A 16.5 percent increase in specific resistance had no effect on the optimum chemical dosages of alum and PACl. A 33 percent increase in specific resistance resulted in a decrease in optimum PACl (w/SO_4) dosage from 42 to 32 mg/L Al_T, but had no effect on the optimum alum dosage. A 68 percent increase in specific resistance resulted in a decrease in optimum Aqualyte 104 dosage from 50 to 30 mg/L and an increase in Magnifloc 572C dosage from 75 to 200 mg/L. A specific trend did not develop between the optimum ferric chloride dosage and specific resistance. As a result of the variations between

Table 3

RAW SLUDGE DATA

SET NO.	COLLECTION DATE	SPECIFIC RESISTANCE m/kg	SUSPENDED SOLIDS %	pH	TOTAL DRY SOLIDS g/L	TIME TO DEWATER 30 mL OF FILTRATE (sec)
1	3/20/85	1.03×10^{12}	0.78	5.85	13.2	430
2	3/27/85	6.91×10^{11}	1.98	6.19	30.1	465
3	5/1/85	1.20×10^{12}	2.64	6.08	27.1	370
4	7/15/85	2.20×10^{12}	2.10	5.62	24.0	690
5	7/22/85	3.30×10^{12}	2.20	5.80	18.1	860
6	8/1/85	4.40×10^{12}	2.50	5.62	33.0	2240

Table 4

SUMMARY OF OPTIMUM CHEMICAL DOSAGES AND TIMES TO DEWATER 30 mL OF FILTRATE

RAW SLUDGE NUMBER		OPTIMUM CHEMICAL DOSAGE AND TIME TO DEWATER 30 mL OF FILTRATE					
		FERRIC CHLORIDE	ALUM	PACl as Al_T	PACl (w/SO_4) as Al_T	AQUALYTE 104	MAGNIFLOC 572C
1	DOSE	200 mg/L	300 mg/L	77 mg/L	--	--	--
	TIME	25 sec	54 sec	28 sec	--	--	--
2	DOSE	300 mg/L	--	--	--	50 mg/L	75 mg/L
	TIME	57 sec	--	--	--	13 sec	78 sec
3	DOSE	250 mg/L	300 mg/L	77 mg/L	--	--	--
	TIME	35 sec	109 sec	50 sec	--	--	--

Table 4
(continuation)

SUMMARY OF OPTIMUM CHEMICAL DOSAGES AND TIMES TO DEWATER 30 mL OF FILTRATE

RAW SLUDGE NUMBER		OPTIMUM CHEMICAL DOSAGE AND TIME TO DEWATER 30 mL OF FILTRATE					
		FERRIC CHLORIDE	ALUM	PACl as Al_T	PACl (w/SO_4) as Al_T	AQUALYTE 104	MAGNIFLOC 572C
4	DOSE	400 mg/L	--	--	--	30 mg/L	200 mg/L
	TIME	56 sec	--	--	--	28 sec	114 sec
5	DOSE	300 mg/L	500 mg/L	--	42 mg/L	--	--
	TIME	34 sec	29 sec	--	11 sec	--	--
6	DOSE	400 mg/L	500 mg/L	--	32 mg/L	--	--
	TIME	39 sec	142 sec	--	42 sec	--	--

the effects of specific resistance on the optimum chemical dosages, a direct correlation between specific resistance and optimum chemical dosage cannot be determined.

Effect of Primary Sludge to Waste Activated Sludge Ratio on Optimum Ferric Chloride Dosage

Although the volumetric ratio of primary sludge to waste activated sludge was constant in the aforementioned experiments, the effect of varying this ratio on the optimum chemical dosage for ferric chloride was examined. In the previous experiments, a volumetric ratio of 7 parts primary sludge to 4 parts waste activated sludge was used. The effects of adding 8 parts and 16 parts of waste activated sludge, respectively, to 7 parts of primary sludge were observed. The results are shown in Figure 8 with a summary of the results listed in Table 5. Increasing the amount of waste activated sludge resulted in a decrease in sludge dewatering time. There was no trend regarding the optimum ferric chloride dosage. Since additional waste activated sludge did not increase dewatering times, our study approach of using a volumetric ratio of 7 parts primary sludge to 4 parts waste activated sludge is actually conservative. The larger ratio of primary sludge to waste activated sludge was selected to provide more consistent sludge properties since Novak (1984) indicated that pure waste activated sludge is difficult to work with and subject to high variability.

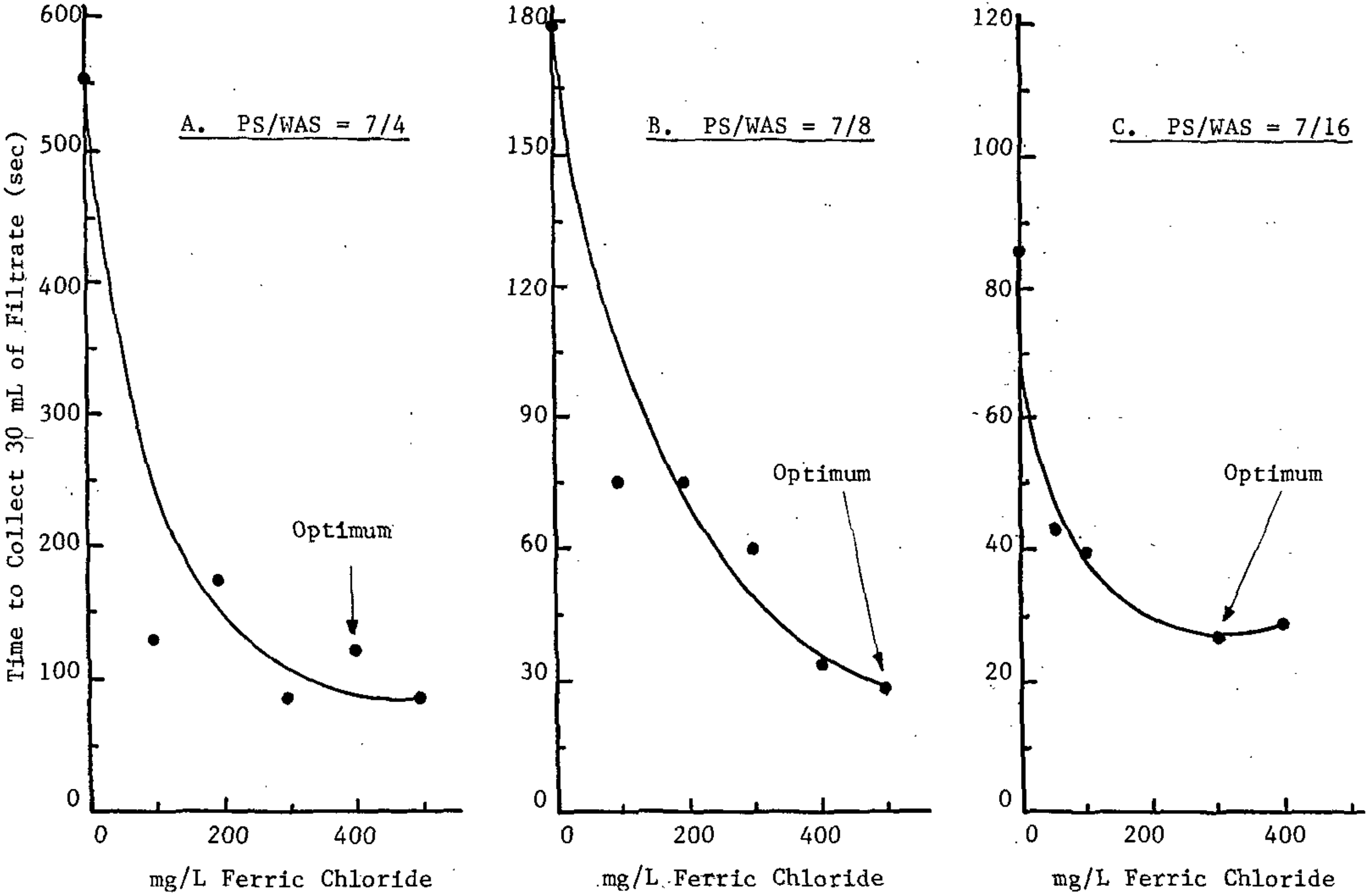

Figure 8. Time to Collect 30 mL of Filtrate vs. Ferric Chloride Dosage (Sludge Dewatering Exp. #7; Effects of varying primary sludge to waste activated sludge ratio on optimum ferric chloride dosage)

Table 5

EFFECTS OF PRIMARY SLUDGE TO WASTE ACTIVATED SLUDGE RATIOS ON OPTIMUM DOSAGES OF FERRIC CHLORIDE

			I	II	III
RAW SLUDGE DATA	PARTS	PRIMARY SLUDGE	7	7	7
		WASTE ACTIVATED SLUDGE	4	8	16
		SUSPENDED SOLIDS, g/L	21.76	18.40	18.44
		SPECIFIC RESISTANCE, m/kg	9.01×10^{11}	3.71×10^{11}	2.27×10^{11}
		TOTAL DRY SOLIDS, g/L	41.08	29.85	21.61
		pH	5.22	5.44	5.56
		OPTIMUM DOSAGE OF FERRIC CHLORIDE	400 mg/L	500 mg/L	300 mg/L
		OPTIMUM TIME TO DEWATER 30 mL OF FILTRATE	62 sec	28 sec	27 sec

Residual Aluminum

Total residual aluminum was measured for experiments involving PACl and alum. The total residual aluminum in the sludges conditioned with alum and PACl from experimental set number 3 are shown in Figures 9 and 10, respectively. The final pH values of these conditioned sludges are also plotted. The initial residual aluminum of the raw sludge in this set of experiments was 1.7 mg/L Al_T. For both alum and PACl, the residual aluminum increased with increasing chemical dosages. From Table 4, the optimum dewatering dosages were 300 mg/L alum and 77 mg/L PACl as Al_T. For these optimum dosages, the total residual aluminum was 3.4 mg/L and 2.2 mg/L for alum and PACl, respectively.

The experiments involving PACl with sulfate produced similar results. In both experiments, the total residual aluminum in sludges conditioned with PACl (w/SO_4) was less than the total residual aluminum in sludges conditioned with alum at respective optimal dosages. From Table 4, the optimum chemical dosages in experiment #5 were 500 mg/L and 42 mg/L Al_T for alum and PACl (w/SO_4), respectively. As shown in Figures 11 and 12, the total residual aluminum for this experiment was 1.5 mg/L and 0.4 mg/L for alum and PACl (w/SO_4), respectively. From Table 4, the optimum chemical dosages in experiment #6 were 500 mg/L and 32 mg/L Al_T for alum and PACl (w/SO_4), respectively. Likewise, Figures 13 and 14 indicate a total residual aluminum of 1.4 mg/L and 0.84 mg/L for alum and PACl (w/SO_4), respectively. In general, the total residual aluminum had a tendency to increase with increasing chemical dosage when

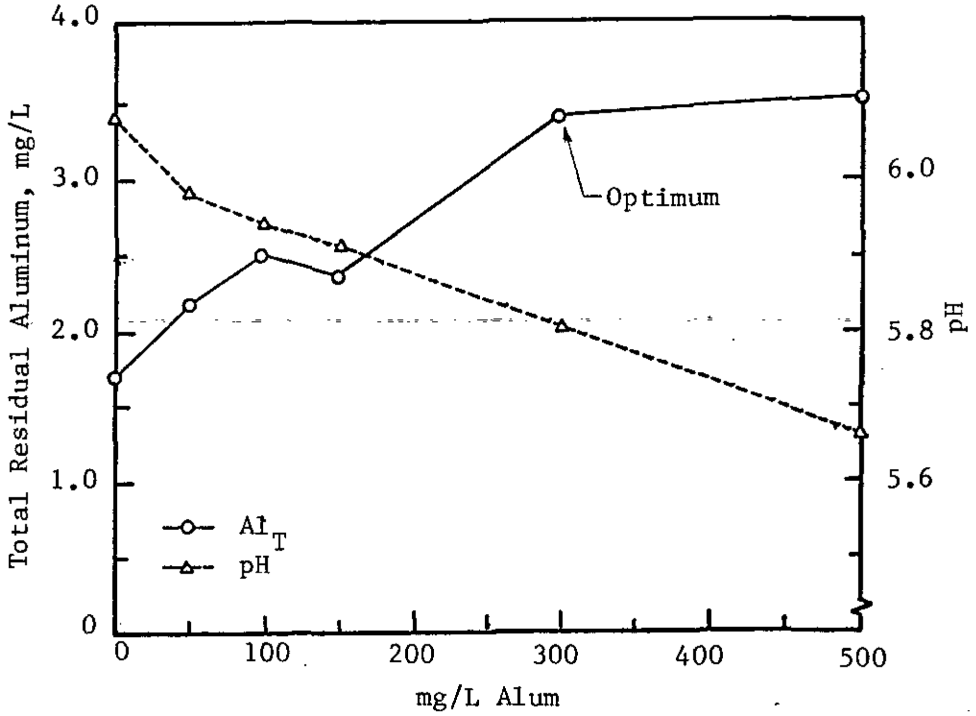

Figure 9. Alum Dosage vs. Residual Al_T and pH

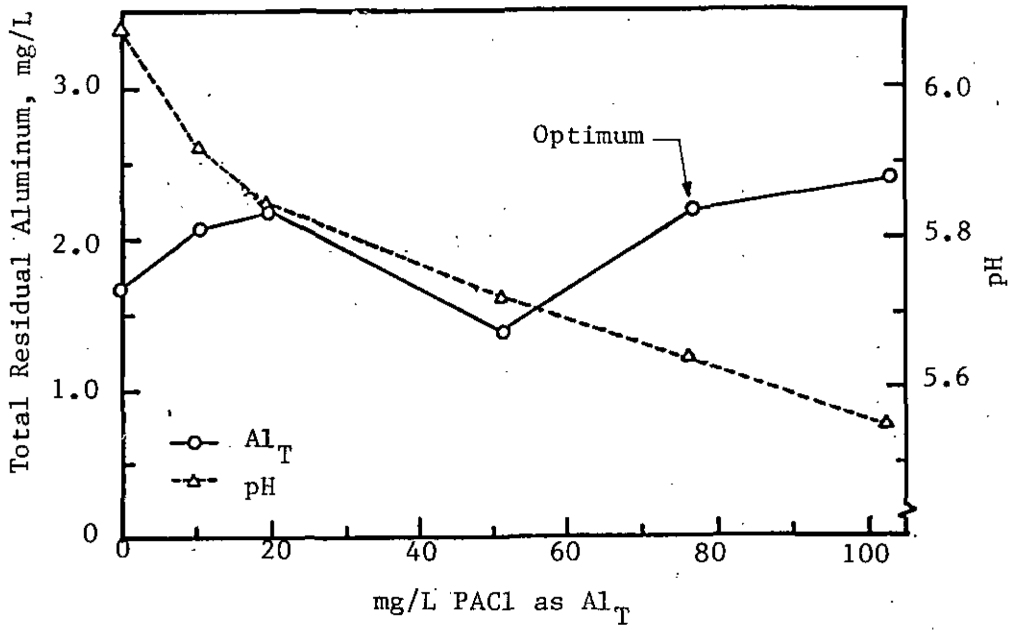

Figure 10. PACl Dosage vs. Residual Al_T and pH
(Sludge Dewatering Exp. #3)

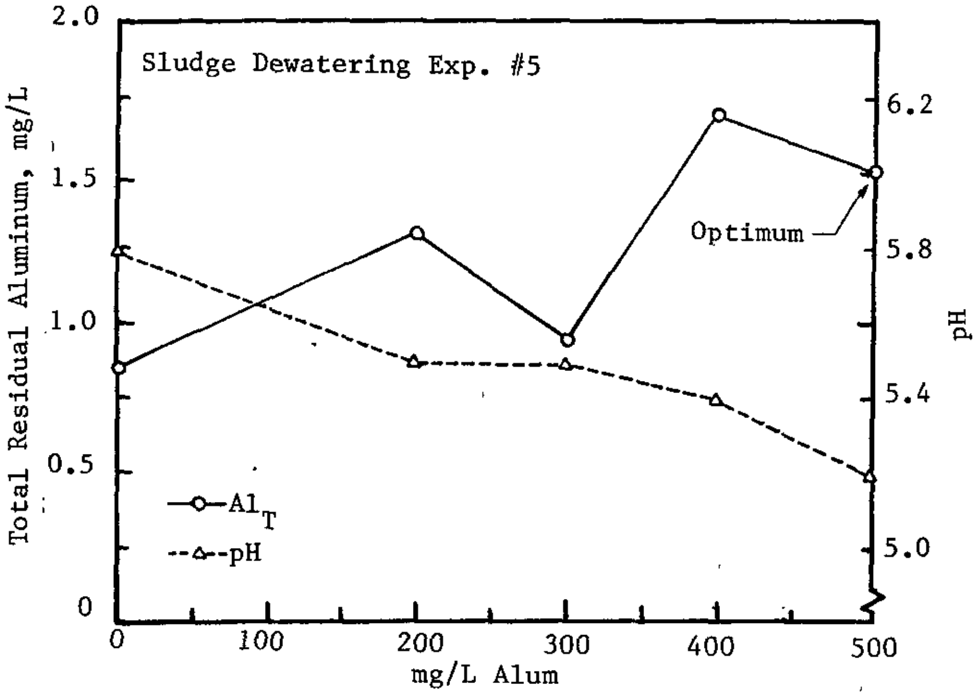

Figure 11. Alum Dosage vs. Residual Al_T and pH

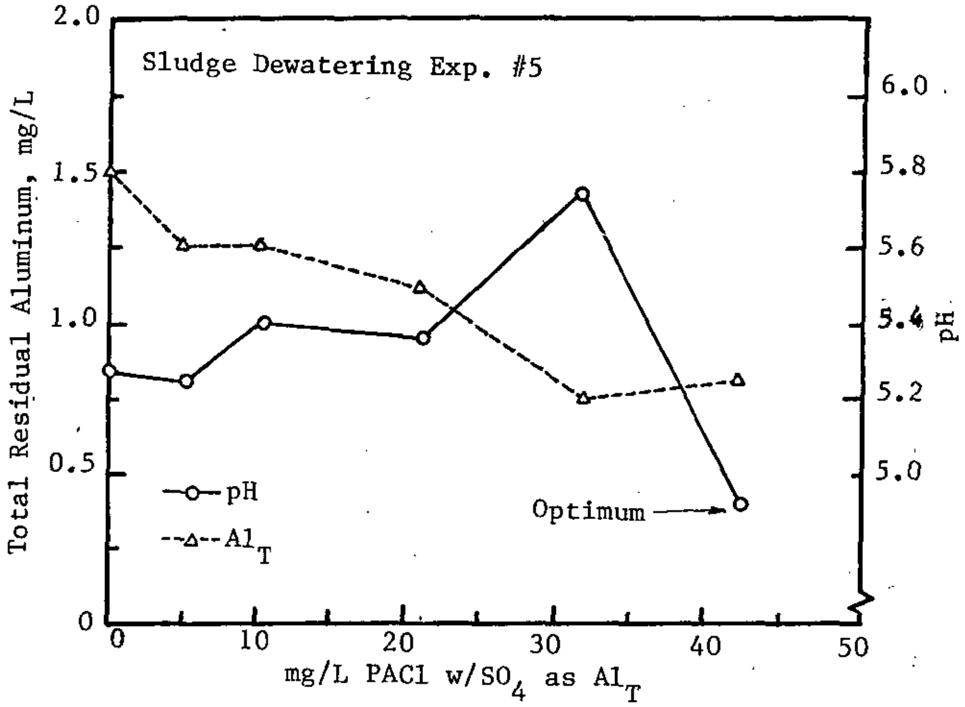

Figure 12. PACl w/SO_4 Dosage vs. Residual Al_T and pH
(Sludge Dewatering Exp. #5)

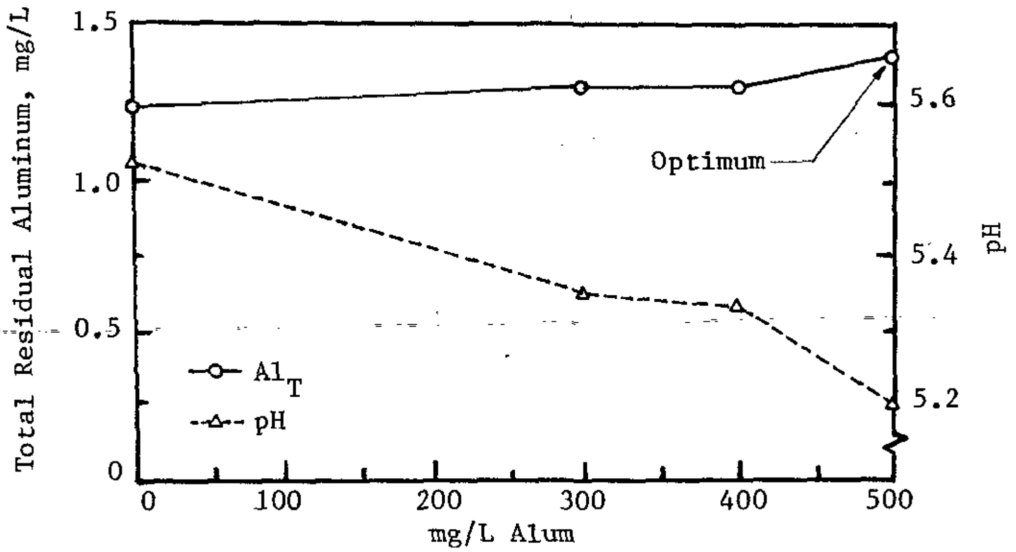

Figure 13. Alum Dosage vs. Residual Al$_T$ and pH (Sludge Dewatering Exp. #6)

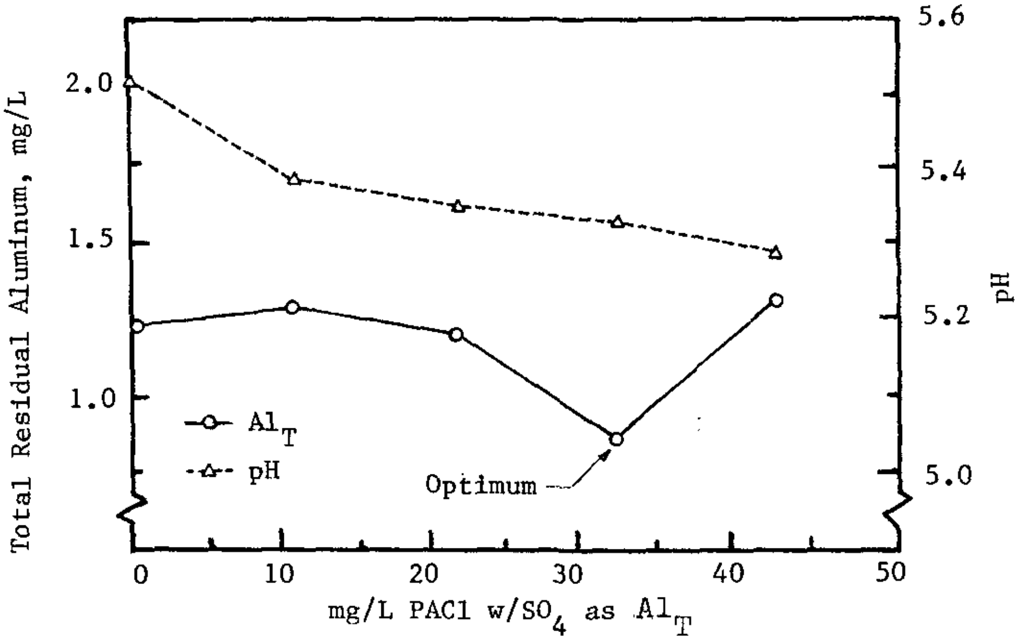

Figure 14. PACl w/SO$_4$ Dosage vs. Residual Al$_T$ and pH (Sludge Dewatering Exp. #6)

the initial total residual aluminum was less than 1.0 mg/L in the raw sludge. However, when the initial total residual aluminum was 1.25 mg/L, the increase in total residual aluminum with chemical dosage was not as significant.

A summary of the total residual aluminum results for the raw sludge, sludges conditioned with alum, and sludges conditioned with both forms of PACl is listed in Table 6. In general, the total residual aluminum in the filtrates of the sludges conditioned with both forms of PACl was less than the total residual aluminum in the sludges conditioned with alum at their respective optimum chemical dosages.

Cost Evaluation

In addition to the dewaterability and residual aluminum factors, the feasibility of considering PACl as a chemical conditioner is also dependent on the chemical costs.The costs of all the chemical conditioners used in the experiments are listed in Table 7. The sources of these costs are also provided in Table 7. The costs of PACl as provided by PPG Industries, Inc. are FOB Barberton, Ohio. The FOB costs are \$0.15 and \$0.085 per lb for PACl and PACl with sulfate, respectively. In order to compare the cost of PACl with the other chemical conditioners, \$0.10 per lb was added for transportation costs to western Massachusetts.

A summary of the estimated chemical costs at the optimum dosages is presented in Table 8. Chemical costs were calculated per gram of solids

Table 6

SUMMARY OF TOTAL RESIDUAL ALUMINUM RESULTS

		EXPERIMENT NUMBER		
		3	5	6
	RAW SLUDGE Al_T RESIDUAL	1.70 mg/L	0.84 mg/L	1.25 mg/L
ALUM	OPTIMUM CHEMICAL DOSAGE	300 mg/L	500 mg/L	500 mg/L
	TOTAL RESIDUAL ALUMINUM	3.40 mg/L	1.50 mg/L	1.40 mg/L
PACl	OPTIMUM CHEMICAL DOSAGE	77 mg/L Al_T	--	--
	TOTAL RESIDUAL ALUMINUM	2.20 mg/L	--	--
PACl (w/SO_4)	OPTIMUM CHEMICAL DOSAGE	--	42 mg/L Al_T	32 mg/L Al_T
	TOTAL RESIDUAL ALUMINUM	--	0.40 mg/L	0.84 mg/L

Table 7

1985 CHEMICAL COST DATA

CHEMICAL	$COST/LB	COST REFERENCES
Alum	0.12	Chemical Marketing Reporter
Aqualyte 104	2.85	Amherst Wastewater Treatment Facility
Ferric Chloride	0.14	Amherst Wastewater Treatment Facility
Magnifloc 572C	1.20	American Cyanamid
Polyaluminum Chloride*	0.25	PPG Industries, Inc.
Polyaluminum Chloride with SO_4**	0.185	PPG Industries, Inc.

* cost FOB = 0.15
** cost FOB = 0.085

Table 8

SUMMARY OF ESTIMATED CHEMICAL COST AT OPTIMUM DOSAGES (\$ x 10^{-6} per gram of solid)

RAW SLUDGE NUMBER	ESTIMATED CHEMICAL COSTS					
	FERRIC CHLORIDE	ALUM	PACl	PACl (w/SO_4)	AQUALYTE 104	MAGNIFLOC 572C
1	10.5	12.0	6.1	--	--	--
2	6.1	--	--	--	20.9	13.2
3	5.7	5.8	3.0	--	--	--
4	10.3	--	--	--	15.7	44.0
5	10.2	14.6	--	2.1	--	--
6	7.5	8.0	--	0.8	--	--

in the raw sludge. As shown in this table, both forms of PACl (with and without sulfate) are cost competitive.

The cost evaluation of PACl in this feasibility study is based on the Buchner funnel test. However, the relative evaluation of chemical dosages based on the Buchner funnel test does not indicate the feasibility of using PACl in filter press dewatering operations. Since filter presses are highly sensitive to incoming feed characteristics, the strength of the conditioned sludge would have to be examined. Thus, future research should examine the use of PACl on a pilot plant scale.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The feasibility of using polyaluminum chloride (PACl) as a chemical conditioner for municipal wastewater sludges was examined in this study through sludge dewatering experiments. A Buchner funnel apparatus was used to measure sludge specific resistance and the time to collect 30 mL of filtrate. The latter measurement was used to evaluate any improvement in sludge dewatering rates from the addition of chemicals. Based on the data collected from these experiments, the following conclusions may be drawn:

1. PACl (with and without sulfate) provides more efficient sludge dewatering results than alum. In the sludge dewatering experiments, PACl provided sludge dewatering times that were at least 50 percent less than the sludge dewatering times of alum. In addition, sludge dewatering times of PACl were similar to sludge dewatering times of ferric chloride, the most commonly used chemical conditioner in wastewater treatment.
2. The high molecular weight organic polymer Aqualyte 104 is a more effective chemical conditioner than the low molecular weight high charge density cationic polymer tested (Magnifloc 572C). Both Aqualyte 104 and PACl gave low sludge dewatering times. The sludge dewatering

results verify the present use of Aqualyte 104 as a good chemical conditioner for the Amherst Wastewater Treatment Facility.

3. Although pH generally decreased with increasing chemical dosages of ferric chloride, alum, and PACl, there was sufficient buffering that the maximum pH drop was 0.6 units. The initial pH of the raw sludges treated ranged from approximately 5.5 to 6.3.
4. A direct correlation between raw sludge specific resistance and optimum chemical dosage was not found.
5. The study made use of a volumetric mixture of primary sludge to waste activated sludge at a ratio of 7/4. Experiments using increasing amounts of waste activated sludge were run, and the results justified the study approach.
6. Total residual aluminum in filtrates of sludges conditioned with PACl (with or without sulfate) was less than the total residual aluminum in the sludges conditioned with alum. In one case, a raw sludge with an initial total residual aluminum concentration of 1.7 mg/L resulted in concentrations of 3.4 mg/L and 2.2 mg/L for alum and PACl, respectively, at their optimum chemical conditioning dosages. In the experiment involving PACl with sulfate, the raw sludge treated had a total residual aluminum concentration of 0.84 mg/L in the first set of

experiments. Total residual aluminum concentrations of 1.5 mg/L and 0.4 mg/L were measured in the filtrates of the sludge treated with alum and PACl with sulfate respectively. In the second set of experiments also involving PACl with sulfate, the total residual aluminum concentration of the raw sludge was 1.25 mg/L. In this case, the total residual concentrations at the optimum dosages of alum and PACl w/SO_4 were 1.40 mg/L and 0.84 mg/L, respectively.

7. The cost evaluation indicates that both forms of PACl are cost competitive with more commonly used chemical conditioners.

Since the efficiency of dewatering equipment such as filter presses is dependent on the proper selection of the optimum chemical dosage of conditioners in relation to the sludge characteristics, the evaluation of PACl based on the Buchner funnel test does not address the use of PACl in filter press dewatering operations. As a laboratory experiment, the Buchner funnel test has its limitations. Optimum chemical dosages vary with particle size distribution. The Buchner funnel test does not regulate particle size distribution. Since the test involves a small filter area, the solids concentration of the sludge may also be sufficient to cause blinding. In addition, the efficiency of sludge dewatering equipment is dependent on the strength of the sludge. Particle resistance to shear should be taken into consideration. High molecular weight polymers are good chemical conditioners because they provide a matrix of particles that dewater easily and have high resistance to shear. However, the Buchner funnel test does not indicate particle resistance to shear. Thus, the following recommendations are made for further study:

1. Factors such as particle size distribution, particle density, and resistance to shear should be evaluated to determine the feasibility of using PACl as a sludge conditioner.
2. Pilot plant studies should be conducted to determine the effectiveness of PACl in filter presses.

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