THE EFFECT OF TREATMENT PROCESS VARIATIONS ON THE THICKENING AND DEWATERING CHARACTERISTICS OF WATER PLANT SLUDGES

by

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(ABSTRACT)

The effects of coagulation pH and influent turbidity on aluminum and ferric hydroxide sludge macro- and micro-properties were investigated. To reduce the number of variables, sludges were produced under specific operating conditions in a 400 L/day continuous-flow pilot-plant. The effluent turbidity was monitored to evaluate process modifications.

Sludge thickening and dewatering characteristics improved with reductions in the coagulation pH, increases in the influent turbidity levels, and/or reductions in the coagulant dose/influent turbidity ratio. Sludge floc/aggregate density was the dominant sludge micro-property; sludges with superior thickening and dewatering characteristics were composed of higher density flocs/aggregates. A trade-off appeared to exist between improved sludge characteristics and effluent quality; however, verification will require additional research.

ACKNOWLEDGEMENTS

I would like to thank Dr. Knocke for the guidance, insight and patience extended to me since my introduction to the program. Appreciation is also expressed to Dr. Novak and Dr. Hoehn for serving on my committee. Finally, special personal thanks go to the author's wife, Raeann, for her patience and encouragement.

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INTRODUCTION

Water-treatment sludges produced during coagulation with metal salts, such as alum and ferric chloride, typically are voluminous, thicken poorly, and are difficult to dewater. As the regulations regarding the disposal of coagulant sludges have become increasingly strict, more importance has been placed on their thickening and dewatering characteristics. Prior to the passage of the Federal Water Quality Act of 1965 and the Federal Water Pollution Control Act Amendments of 1972, water-treatment plant wastes often were simply discharged into the nearest body of water. These laws subsequently classified water-treatment sludges as pollutants and, as such, required controlled ultimate disposal, usually accomplished by landfilling. In order for this to be economically feasible, thickening and/or mechanical dewatering of the sludge is usually necessary.

Costs associated with sludge handling can be reduced by two approaches. First, the quantity of sludge produced can be reduced by the use of polyelectrolytes as either primary coagulants or as flocculant aids, replacing a portion of the metal salt dosage. However, due to the long-standing success associated with the use of inorganic coagulants, the majority of water-treatment facilities continue to employ inorganic coagulants, particularly alum.

An alternate approach to reducing sludge-handling costs involves the alteration of sludge characteristics to facilitate thickening and dewatering. Various methods proposed in the literature include freeze-thaw, heat, and polyelectrolyte conditioning. There are few references in the literature, however, linking treatment process operating conditions with sludge characteristics. Treatment optimization studies in the past have considered only turbidity and organics removal efficiencies, leaving sludge quantity and dewatering characteristics as dependent variables. Clearly, the need for an integrated view of coagulation and sludge formation exists. Therefore, the following objectives were proposed for this study:

(1) to determine the effects of pH and influent solids concentrations on the thickening and dewatering characteristics of aluminum hydroxide and ferric hydroxide sludges;

(2) to correlate treatment efficiency, as measured by effluent turbidity, and sludge characteristics for both coagulants over a range of coagulation pH values typical of full-scale operations; and

(3) to investigate the role of sludge-particle size and water content in defining these thickening and dewatering characteristics.

LITERATURE REVIEW

This chapter contains a review of the literature pertinent to the effects of operating parameters on the thickening and dewatering characteristics of water plant sludges. Brief reviews of both coagulation and floc formation theory are included, as both subjects pertain to the fundamental sludge particle and, thus, to sludge characteristics. A chronological literature review of water plant sludge dewatering studies is presented to lay the foundation from which this study developed. Finally, methodologies used in this study are reviewed from a sludge-testing perspective for both merit and limitations.

Coagulation Theory

Many attempts have been made by researchers to further the understanding of the mechanisms of coagulation involved when using metal coagulants. Stumm and Morgan (1) reviewed existing coagulation theory and concluded that the process was indeed complex. The need for a chemical theory that incorporated pH, buffering capacity, coagulant and colloid equilibria, and complexation effect was reported. Emphasized, however, was the importance of pH due to its effect on both the coagulant hydrolysis products and the charge of colloidal material.

A more complete understanding of coagulation based on experimental evidence was presented by Stumm and O'Melia (2). Destabilization of colloidal material by metal coagulants was proposed to be a result of the hydrolysis of metal ions and subsequent adsorption of these hydrolysis species onto colloidal surfaces. Aggregation of destabilized particles was attributed to a combination of mechanisms including interparticle bridging by polymerized hydrolysis species, entrapment in precipitating metal hydroxides, and van der Waals forces. Particle transport was considered to be an important factor in the aggregation of destabilized particles. Unlike the complex coagulation model of the future proposed previously by Stumm and Morgan (1), Stumm and O'Melia (2) simplified coagulation to a system controlled by coagulant dose, pH, and colloid surface area. Of importance to this thesis, a need was expressed by Stumm and O'Melia for future research of the physical properties of sludge flocs such as filtrability, shear strength, density and compressability. Also suggested was the interdependence of subsequent treatment processes such as thckening, filtration and sludge disposal with the coagulation process. An excellent review of the coagulation process, composed primarily of the previous work with Stumm, was presented by O'Melia (3). Included in the review were proposed treatment schemes for four types of water, classified according to alkalinity and particulate surface area.

Of major practical value to both this study and water-treatment practice is the stability-coagulation diagram for alum presented initially by Amirtharajah and Mills (4), and the like diagram for ferric chloride presented by Johnson and Amirtharajah (5). These diagrams (see Figures 1 and 2) were developed by combining results from the authors' testing with numerous results in the literature and less complete diagrams such as those developed by Rubin and Blocksidge (6). These diagrams deliniate condition regions where the various modes of coagulation predominate. In Figures 1 and 2, the regions over which expermentation for this study occurred have been noted. As illustrated by these diagrams, coagulation efficiency was proposed to be a function of only two independent variables, namely pH and coagulant dosage (4,6). Amirtharajah and Mills (4) also showed experimentally the importance of mass transport in destabilization during coagulation by adsorption for charge neutralization.

Two additional aspects that have been researched are electrostatic and anion effects. Though proposed as a control parameter for water treatment (7), the electrical surface charge associated with particles has been shown to inconsistently correlate with coagulation efficiency (8,9), with optimum coagulation usually occurring at a somewhat negative particle charge (9). Because optimum coagulation often does not occur at zero particle charge, and charge

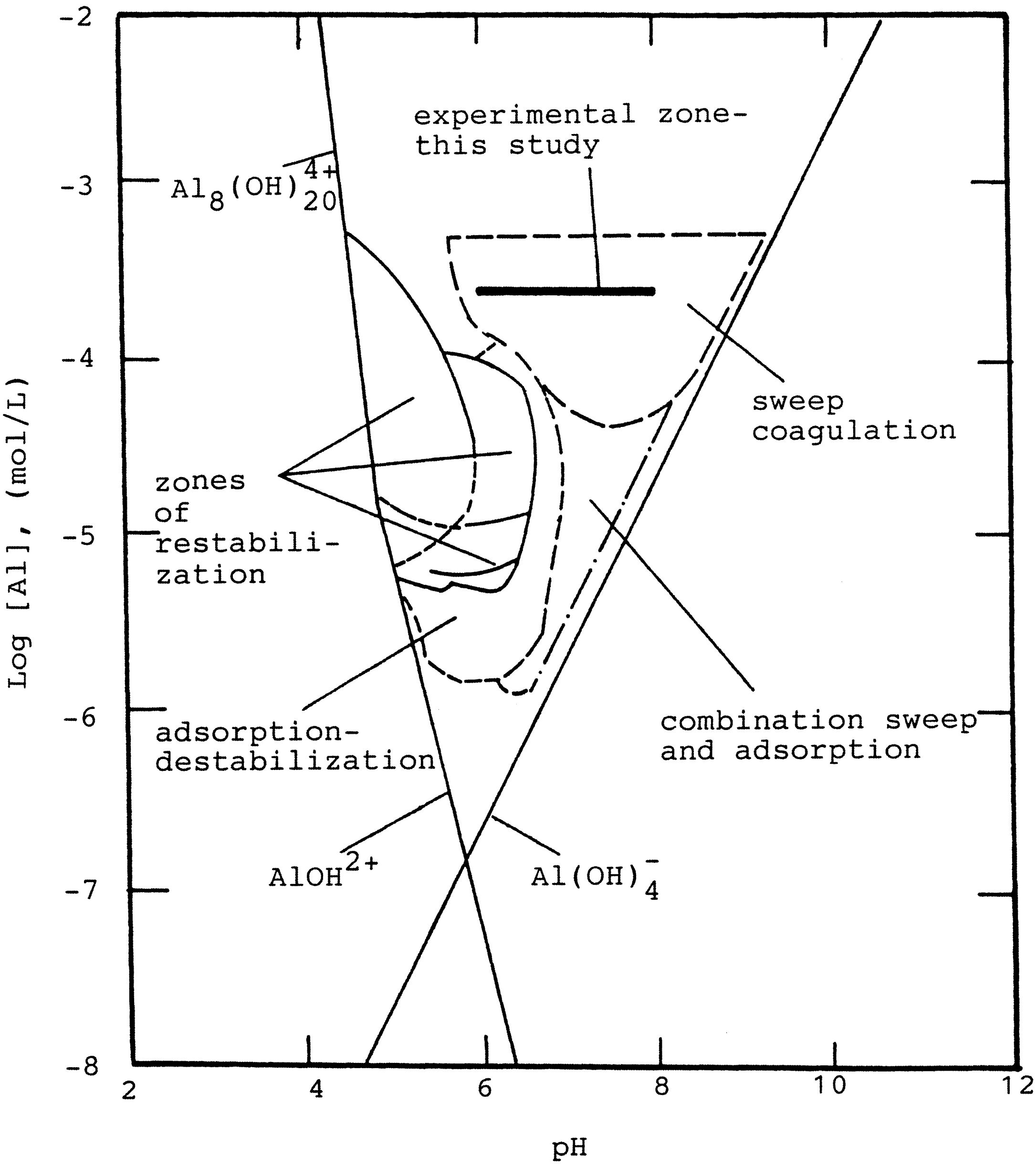

Figure 1: Stability-coagulation diagram for aluminum salts. After Johnson and Amirtharajah (5).

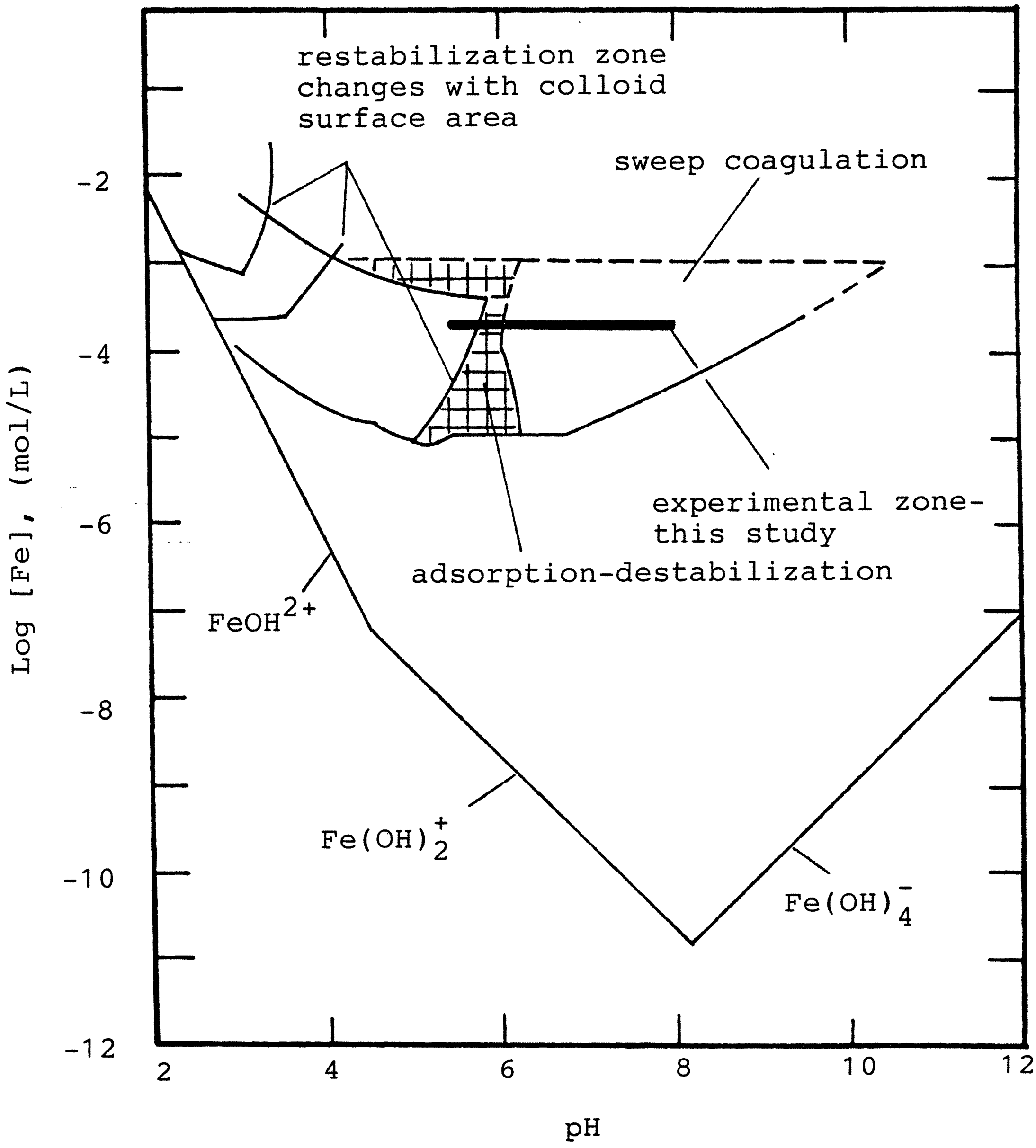

Figure 2: Stability-coagulation diagram for iron salts. After Johnson and Amirtharajah (5).

reversal of particles does occur, it has been suggested that chemical interactions take precedence over electrostatic phenomena (2,10).

The effects of chloride and sulfate, the anions pertinent to this study, on floc formation (11) and the pH of the maximum precipitation (12) showed chloride had little effect. However, sulfate broadened the pH zone of "rapid floc formation" (11), lowered the pH of maximum precipitation (12), and eliminated particle restabilization under certain circumstances (13). The meaningfulness of some of these results maybe suspect. For example, the experimental methods of Black et al., (11) might be considered qualitative at best. Also, there is no correlation between optimum coagulation and maximum precipitate formation, the measured parameter used by Marion and Thomas (12).

Floc Formation

In addition to efficient coagulation, solid-liquid separation must be optimized for effective water treatment. This can be accomplished by increasing the size and/or density of the particles produced during coagulation. Changes in the physical characteristics of particles effect thickening and dewatering of the resultant sludge as well.

Floc size is a function of the chemical and physical conditions under which the floc are formed. Hudson (14) reported that denser floc were produced during flocculation with more intense mixing. Hannah _et al_., (15), after testing the resistance of floc to mechanical shear, suggested that the quickest forming floc were not necessarily the strongest, and that floc that contained more kaolin appeared stronger. The ability of certain polyelectrolytes to increase floc size and strength was also reported.

Ham and Christman (16) conducted extensive testing of alum sludge floc size distributions produced as a function of process variables and time. Important findings included:

1) the rate of coagulation increased with increased suspended material;
2) floc breakage is primarily due to interparticle collisions, rather than hydraulic shear;
3) floc settling rates increased with decreasing pH or alum dose; and
4) stronger, larger floc are produced at pH 8.1, than at a pH of 7.1 or 9.1.

In limited testing using ferric chloride as a coagulant, Ham and Christman found that ferric hydroxide floc were stronger and larger than aluminum hydroxide floc. In general, it was concluded that certain aspects of coagulation and floc formation could be optimized, usually at an expense of others.

In an attempt to simulate the flocculation process, computer models were developed by Vold (17), Fair and Gemmel

(18), and Sutherland (19). The model developed by Fair and Gemmel (18), assumed the formation of spherical particles; an assumption that limited the model's application to real situations. The models by both Vold (17) and Sutherland (19) predict a decrease in floc density as floc size increases. Lagvankar and Gemmel (20) reported that the density of iron (III) flocs did decrease with increasing floc size, and that increased agitation during flocculation produced smaller floc that were not significantly different in density, size-for-size, than those produced with less intense mixing. However, Vollrath-Vaughn (21) later found that the sucrose settling method used by Lagvankar and Gemmel (20) to measure floc density might be inappropriate, thus leaving their results open to question.

<u>Water Treatment Plant Sludge Characterization</u>

Previous to the late sixties, few restrictions were placed on the disposal practice of water treatment sludges. Until that time, sludges were often discharged to lakes or streams with little concern about the quantity or characteristics of the solids discharged.

However, in the face of impending regulation, studies were conducted to characterize water plant sludges and propose volume reduction practices. Gates and McDermott (22) concluded that alum sludge was composed primarily of settleable solids, had non-Newtonian flow characteristics, and was subject to zone settling and compaction. Solids analysis revealed 24-35 percent to be volatile, and 92-98 percent were suspended solids. The specific resistance test was considered an adequate method for determining both the filterability of sludge and the effect of polyelectrolyte conditioning. Filtrability of the alum sludge was reported as similar to that of primary sewage sludges.

Sludge characterization done by Neubauer (23) showed alum sludge to have a low total solids content, a low solids density, and an inability to settle to concentrations suitable for handling with earthmoving equipment. The BOD of the sludge ranged from 36-77 mg/l while the COD typically ranged from 500 to 1000 mg/l. Suspended solids were reported to be 84 percent of the total solids.

Faced with the newly acquired importance of sludge management, the American Water Works Association Research Foundation published a series of reports (24) in 1969 detailing the current status of knowledge, technology, costs and ideas for the future. Removal of water from sludge by mechanical means or by conditioning of the sludge was reviewed in great detail. However, no mention was made of reducing sludge water content by adjusting operating conditions. Ideas proposed for future research included further characterization of sludges and the development of meaningful testing parameters, but neglected the role of operating conditions in the formation of sludge (25).

Novak *et al.*, (26) tested sludges from numerous water treatment plants in Missouri, resulting in several interesting conclusions. Sludges containing softening precipitates settled to much higher solids concentrations, had lower specific resistance values, but had to be dewatered to much higher solids concentrations to be handleable. Sludge filtrability was found to decrease as the percentage of coagulant in the sludge increased. Most notable, however, was the correlation between the settled solids concentrations and the dewatering characteristics of the sludges.

Glenn *et al.*,(27) reviewed coagulation theory pertaining to alum and conducted fundamental research with aluminum hydroxide sludge using the specific resistance test. The specific resistance values were found to be dependent upon the initial solids concentration of the sludge, contrary to dewatering theory. Also, the specific resistance increased with increasing applied vacuum, suggesting that aluminum hydroxide sludge floc were compressible. The specific resistance of aluminum hydroxide sludge was also decreased by recycling previously formed sludge through the treatment process as a sort of "crystal seeding".

Calkins and Novak (28), expanding the work done previously by Novak *et al.*,(26), reported an increase in the settled solids concentration attained for sludges formed from turbid waters than from less turbid waters. Changes in the characteristics of metal coagulant sludges occurred with time. As ferric and aluminum hydroxde sludges aged, both specific resistance values and settled solids concentrations increased. Because of the positive effect of turbidity on sludge characteristics, the authors recommended the use of single-stage coagulation units. This is significant as it was the first mention of treatment process variation for the improvement of sludge dewatering characteristics.

The effects of floc size and polymer addition on the thickening and dewatering properties of metal hydroxide sludges were investigated by Knocke et al.,(29). The addition of polymer, regardless of charge, increased particle size, therefore improving both the thickening and dewatering rates of the sludges. However, polymer addition seemed to have no effect on the ultimate settled solids concentration after thickening. This, combined with the fact that the slopes of the log settling velocity versus initial solids concentration curves did not change significantly, led the authors to conclude that little change in floc density occurred when polymers were added to the sludge. The interpretation of the log settling velocity versus initial solids concentration plot with regard to sludge density was proposed by Novak (30), as cited by Knocke et al., (29). Novak et al., (31) reported that the use of polymers increased sludge particle size, therefore increasing the dewatering rates. However, no reduction in final cake water content was realized.

After testing was performed on a variety of sludges, Knocke and Wakeland (32) concluded that the dewatering rates of chemical sludges were effected by the size distribution and shape of the particles. A definite correlation was shown to exist between sludge bulk density and both final cake and settled solids concentrations. The authors proposed that both finished water quality and the characteristics of the sludge produced be considered when optimizing treatment processes.

Sludge Thickening Test Procedures

Batch thickening tests are often used to assess the ability of sludges to settle and compact by gravity alone. A review of gravity thickening, incorporating the results of batch thickening tests in the design of continuous thickeners was presented by Dick (33,34). Problems associated with batch thickening results include wall effects of the settling vessel (which can be reduced by slow stirring) and differences in the effective depths of the test and full-scale thickeners (34). Although discrepancies have been reported betwen batch and continuous thickening studies (33-35), and other methods have been proposed to more accurately test sludge for continuous thickener design (35), batch thickening tests do permit comparisons of the basic settling properties of various sludges.

Settling rates are often felt to be a function of aggregate size and density. However, floc volume concentration and attractive forces between flocs (36), size and shape of primary particles and interparticle bonding strength (37), and the size distribution of the settling solids (38), have been found to influence zone settling rates of various suspensions.

For the comparison of zone settling rates of sludges, the simplist involves plotting log settling velocity versus the initial solids concentration. Javaheri and Dick (39) reported that zone settling rates could also be used to calculate the aggregate volume index (AVI) of activated sludge. The AVI is an indicator of the water content or density of the sludge particles, two parameters which are difficult to measure directly.

Javaheri and Dick (39) based their AVI derivation upon the work of Richardson and Zaki (40) which described the settling rates of suspensions consisting of uniformly sized particles by the following equation:

$$V_c/V_o = E^n \qquad (2\text{-}1)$$

where V_c is the suspension interface settling velocity, V_o is the Stokes' Law settling velocity of a single spherical particle, E is the suspension porosity, and n is an emperical constant. Assuming laminar flow and negligible wall effects, Richardson and Zaki found n to equal 4.65. Substituting $(1-I_a)$ for E, Equation 2-1 was rewritten as:

$$V_c/V_o = (1-I_a)^{4.65} \qquad (2\text{-}2)$$

where I_a is the aggregate volume fraction. V_o for an aggregate was defined using Stokes' Law as:

$$V_o = \frac{g(\rho_a - \rho_w)d^2}{18\ u_w} \qquad (2\text{-}3)$$

where g is the acceleration due to gravity, ρ_a is the density of the aggregate, ρ_w is the density of water, u_w is the viscosity of water and d is the average aggregate diameter.

The AVI was defined as the ratio of aggregate volume to dry solids volume, or:

$$AVI = I_a/I_k \qquad (2\text{-}4)$$

where I_k is the dry solids volume fraction. By substituting this into Equation 2-2, Javaheri and Dick described the settling of aggregate suspensions as:

$$V_c = V_o(1-(AVI)I_k)^{4.65} \qquad (2\text{-}5)$$

This was then rewritten as:

$$V_c^{1/4.65} = V_o^{1/4.65} - V_o^{1/4.65}(AVI)I_k \qquad (2\text{-}6)$$

Since both V_c and I_k could be obtained by laboratory testing, Javaheri and Dick calculated sludge AVI values using Equation 2-6. By plotting $V_c^{1/4.65}$ versus I_k, the AVI was determined by dividing the slope of the plot by the y-intercept. Using this technique, Vollrath-Vaughn (21) found the AVI to be applicable for describing the behavior of aluminum and ferric hydroxide sludges.

Sludge Dewatering Test Procedures

Specific resistance has long been used as a measure of the dewatering characteristics of sludges. For an excellent review of the development of the specific resistance equations, the reader is referred to the work of Gale (41) and Vesilind (42). The necessary data for this analysis are obtained from standard Buchner funnel tests, the methodology for which is presented in the next chapter of this thesis.

Gates and McDermott (22) concluded that the specific resistance test was applicable to the analysis of water treatment sludges. Since that time, it has been employed numerous times for such analyses. One of the limitations of the test is the apparent dependence of specific resistance values on the solids concentration of the sludge when blinding occurs (43). This apparent dependence has been noted during the testing of alum sludge (27). Also, the applicability of specific resistance results to predict dewatering capabilities of various types of equipment is limited because the test does not account for the pick-up, release, and scrolling properties of waste sludge (43).

Particle Counting Techniques

The introduction of automatic particle counters has provided insight into the coagulation process, and promoted an integrated approach to water treatment. Particle counting has been found to be more sensitive to larger particles than nephelometry and has provided a new means of process-control technology (44). Tate and Trussell reviewed various methods of particle counting including the light blockage method used in this study (45). The use of particle counters has been proposed as a means of selecting and optimizing water treatment process schemes (45-48).

Particle counting has also been applied to sludge testing and characterization. Knocke (49) and Knocke et al., (50) correlated specific resistance values with particle size and specific surface area for heavy-metal hydroxide sludges. Correlations also existed between sludge thickening rates and characteristic floc size (49). It was concluded that the particle counting technique was useful for determining the relative size distribution of sludge particles; however, absolute count accuracy was seriously doubted (49). In a similar study, Knocke and Wakeland (32) found the same relationship existed between particle size and dewatering rates of water treatment sludges. Therefore, it is evident that particle counting can be helpful in analyzing both treatment efficiency and sludge characteristics.

METHODS AND MATERIALS

To obtain metal hydroxide sludges produced under specific operating conditions, on-site generation of sludge was necessary. The equipment and methods used to produce the sludge are described in the following section. In addition, brief descriptions of the laboratory procedures used to evaluate the sludge are included.

Experimental Procedures

Sludges were generated using a Plexiglas reactor consisting of a rapid-mix basin, a baffled, three-stage flocculation basin, and a clarifier (see Figure 3). The reactor was operated at a fixed flow rate of 400 liters per day. This was accomplished with a constant head tank and a fixed-aperture constriction preceding the rapid-mix tank. The mean hydraulic residence times of the rapid mix tank, flocculation basin and clarifier were two minutes, fifteen minutes, and fifty-five minutes, respectively. Baffles were placed at the inlet and the outlet of the clarifier to prevent short-circuiting.

A high-speed stirrer was used to provide intense, rapid-mixing conditions. Water in the three sections of the flocculation basin was stirred at a constant rate of 45 rpm with three paddles of a six-paddle jar-test apparatus. Alum and ferric chloride were used as coagulants. The feed

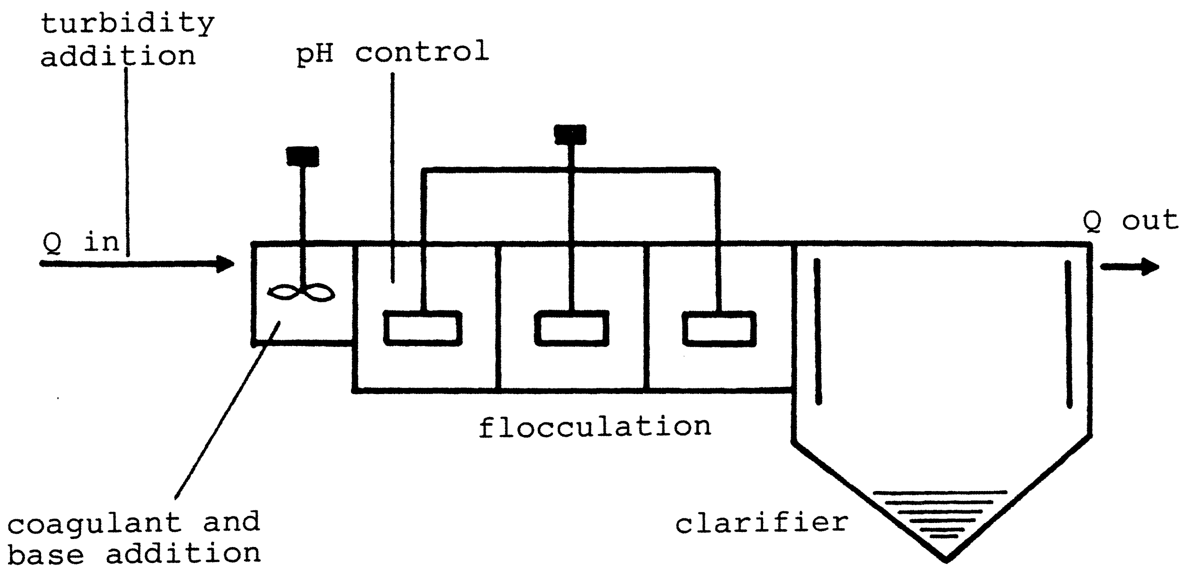

Figure 3: Experimental reactor configuration.

concentration of both metal ions was 0.24 mM, corresponding to 80 mg/L (alum), and 39 mg/L (ferric chloride). These coagulant doses were based on jar tests with alum and the need to maximize sludge production. The concentrations of the stock solutions were 0.012 M and 0.024 M for alum and ferric chloride, respectively.

Coagulation pH values ranged from 5.6 to 8.4 and were maintained using a 0.063 M solution of sodium hydroxide. Both the coagulant solution and the solution used to modify the pH were added directly to the rapid mix tank. Influent turbidities of either 7 or 50 NTU were maintained by the addition of a pre-wetted kaolin suspension prior to the rapid-mix tank. The concentrations of the stock kaolin suspension ranged from 0.7 to 2.2 g/L, depending on the rate of the feed pump. All feed solutions and suspensions were stored in 20-L carboys and continuously fed to the reactor by Cole-Parmer (Chicago, Illinois) metering pumps. Kaolin suspensions were mixed continuously with compressed air to insure uniformity.

Daily testing to insure consistent operating conditions in the reactor included checks of the flow rate, pH, feed solution flow rates, effluent turbidity, and water temperature. Coagulation pH was measured in the first stage of the flocculation basin with a Fisher Scientific (Springfield, New Jersey) Accumet Model 230 pH meter equipped with a combination electrode. Turbidity was determined with a Hach (Loveland, California) Model 2100A turbidimeter. Sludge was siphoned from the clarifier when quantities sufficient for testing (1-2 L) had accumulated. Sludge characteristics were determined by tests described in the following sections.

Analytical Techniques

Solids Determination

Solids concentration (percent by weight) was calculated by dividing the dry-sludge weight by the wet-sludge weight and multiplying by 100. Wet-sludge weight was determined by finding the difference in weight of an aluminum pan before and after receiving a sample of wet sludge. Samples were then dried at 103^{o} C for 24 hours, cooled, and reweighed. Dry-sludge weight was determined by subtracting the weight of the pan from the weight of the dried sample.

For dilute sludge samples, 10- mL samples of sludge were pipetted into pre-weighed aluminum pans, dried at 103^{o} C for 24 hours, cooled, then weighed. The dry-sludge weight was determined as described previously. The solids concentration was then calculated by multiplying the dry-sludge weight by ten. The error introduced by this technique is negligible for dilute sludges. Duplicate samples were tested and the average value reported.

Settled Solids Concentration

To determine the settled-solids concentration, a one-liter sludge sample of known solids concentration was placed in a one-liter graduated cylinder and allowed to settle undisturbed for 24 hours. The settled-solids concentration was then calculated by dividing the initial solids concentration by the fractional volume occupied by settled sludge after 24 hours.

Sludge Dry Solids Density

A glass, specific gravity bottle, designed for use with viscous fluids, was used to determine the specific gravity of a sludge sample. The specific gravity (SG) of a sludge sample was calculated by using the equation:

$$SG = \frac{c-a}{b-a} \qquad (3\text{-}1)$$

where a is the weight of the empty glass bottle, b is the weight of the bottle filled with room temperature water, and c is the weight of the bottle filled with room temperature sludge.

Sludge solids density (ρ_k) was then calculated by using the equation:

$$\frac{100}{\rho_p} = \frac{(100-C)}{\rho_w} + \frac{C}{\rho_k} \qquad (3\text{-}2)$$

where C is the sludge-solids concentration (percent by weight), ρ_w is the density of water at room temperature, and

ρ_p is the bulk density of the sludge ($SG\rho_w$).

Sludge Dewatering

The specific resistance test was used to determine the relative dewatering characteristics of water-plant sludges. This test was conducted using a vacuum pump, and a 9.0 cm Buchner funnel fitted with a Whatman No. 40 ashless filter paper, assembled as shown in Figure 4. A vacuum of 15 inches mercury and 100 mL volume of sludge were used in all tests. The vacuum was applied and the sludge poured over the filter. Though not standard procedure, this was done to avoid the significant leakage of sludge which occurred if the sludge was poured onto the filter before the vacuum was applied. The volume of filtrate was measured and recorded as a function of dewatering time.

The data were analyzed by plotting time divided by the volume of filtrate (t/V) versus volume V, as shown in Figure 5. The slope, b, of the linear portion of the resulting plot was used in the calculation of the specific resistance r in the equation:

$$r = \frac{2PA^2b}{uW} \tag{3-3}$$

where P is the pressure difference across the filter and cake (N/m^2), A is the surface area of the filter (m^2), and u is the viscosity of the sludge (Ns/m^2). The viscosity of the sludge was assumed to be equal to water at the same

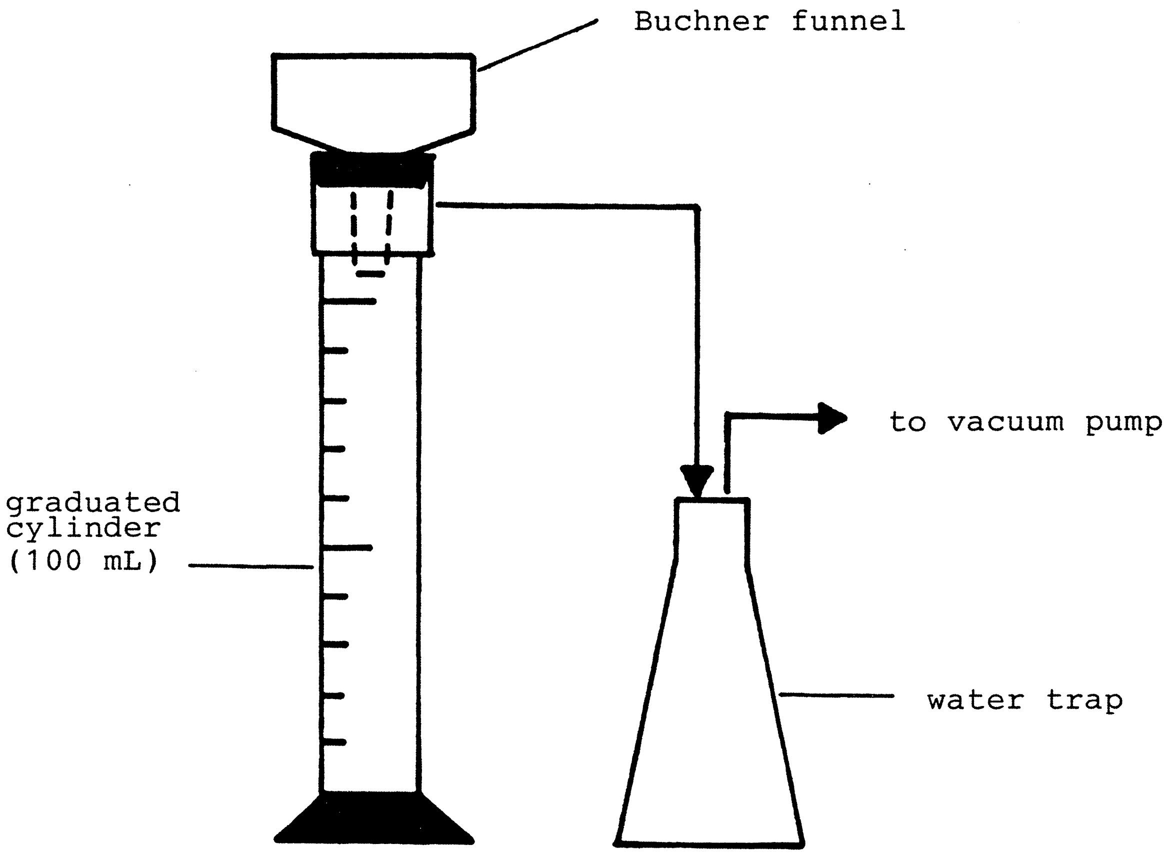

Figure 4: Buchner funnel assembly.

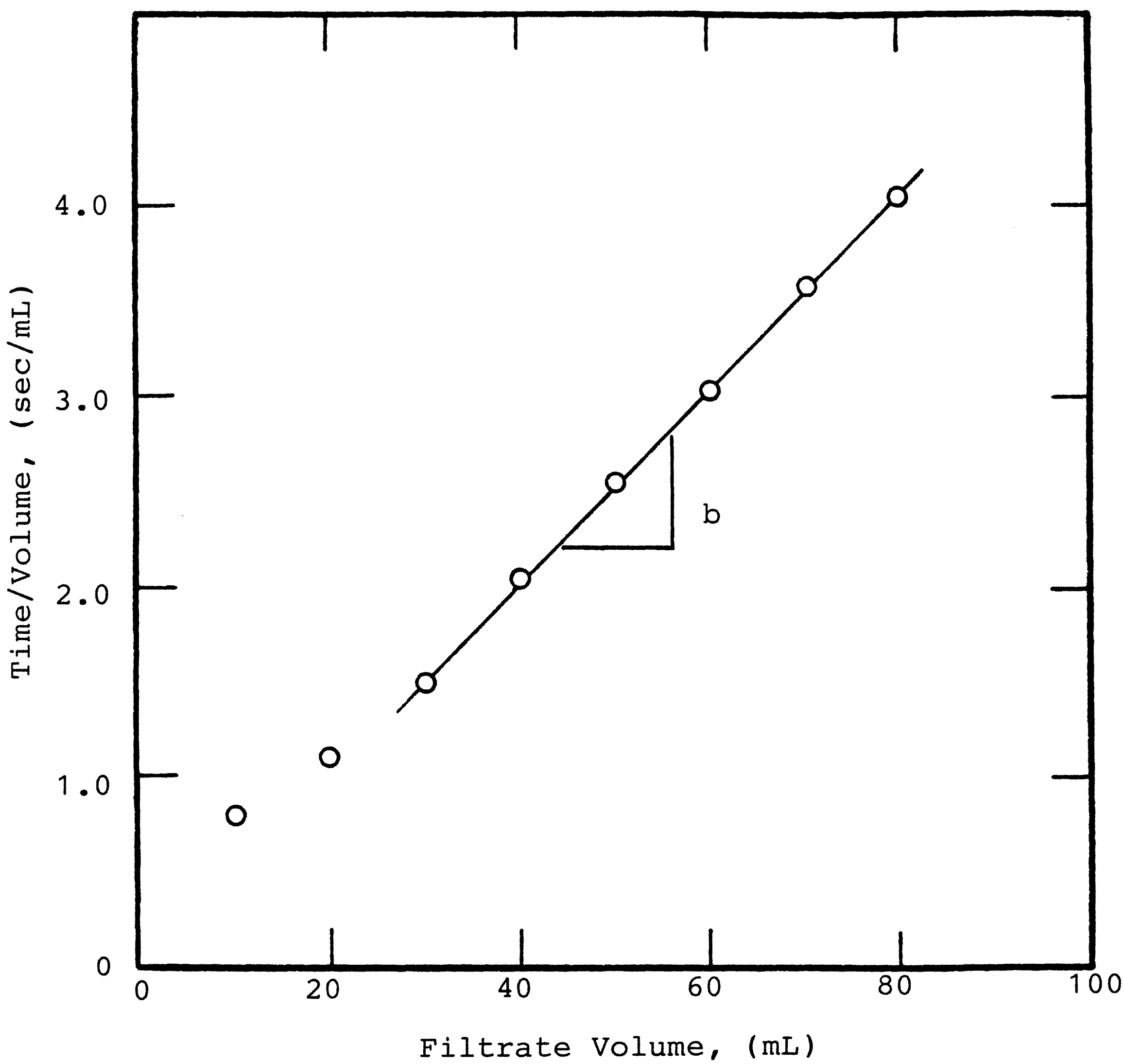

Figure 5: Sample plot of time/volume versus volume used for determining sludge specific resistance values.

temperature. The quantity of solids deposited per unit volume of sludge (W), expressed in terms of kg/m^3, was calculated by using the equation:

$$W = \frac{10(C_k C_o)}{(C_k - C_o)} \qquad (3\text{-}4)$$

where C_o is the initial solids concentration (percent by weight) and C_k is the final cake solids concentration (percent by weight). A minimum of five tests was conducted for each sludge tested. A microcomputer was programmed to calculate specific resistance values based upon a defined data base (t, V, C_k, C_o and P). Specific resistance values were reported in units of m/kg.

Sludge compressibility was also determined by a variation of the specific resistance test. Specific resistances were determined at applied vacuums of 8, 12, 15, 20, and 25 inches mercury. A plot of log(r) versus log(P) yielded a line with slope equal to the coefficient of compressibility (s), as described by Vesilind (41).

Sludge Thickening

A series of at least six, batch, thickening tests were used to evaluate the thickening characteristics of sludge samples. Sludge of known solids concentration was poured into one-liter graduated cylinders in quantities ranging from 100 to 350 mL. The cylinders were then filled to the one-liter mark with sludge supernatant, forming six different suspensions of known solids concentration. After mixing, the suspensions were allowed to settle. During the settling process, the sludge-liquid interface height was recorded as a function of settling time.

The data collected were analyzed by plotting sludge interface height as a function of time. The slope of the linear portion of this plot represented the settling velocity (V) of the sludge at an initial suspended solids concentration C_o (see Figure 6). Log V was then plotted versus C_o, and the resulting linear relationship used to evaluate sludge thickening rates for a given coagulant sludge under a defined set of treatment operating conditions. Thickening data were also used to calculate the AVI proposed by Javaheri and Dick (39). Plots were made of $V^{1/4.65}$ versus the volume fraction of solids (C_o/ρ_k) and a line fitted through the data. The slope of this line divided by its y-intercept is defined as the AVI. A sample plot is shown in Figure 7.

Particle Size Determinations

Sludge particle-size distributions were measured using a HIAC (Menlo Park, California) Model PC-320 particle size analyzer and Model HR-120HC particle sensor. These instruments were used to count the number of particles ranging in size from 2 to 120 microns in a 10-mL sample. When necessary, samples were diluted with filtered reactor

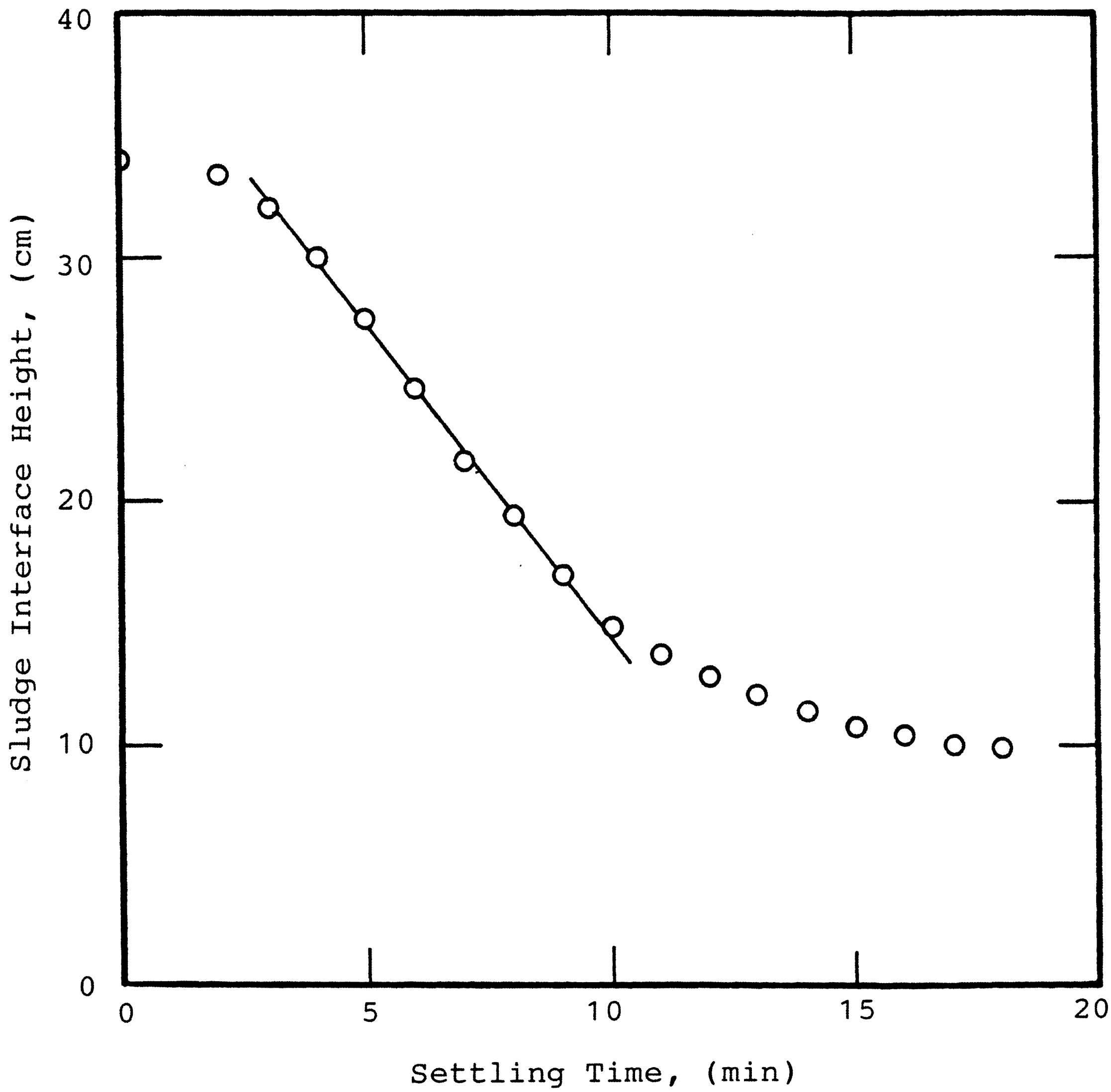

Figure 6: Sample plot of sludge interface height versus time used to determine the sludge zone settling velocity.

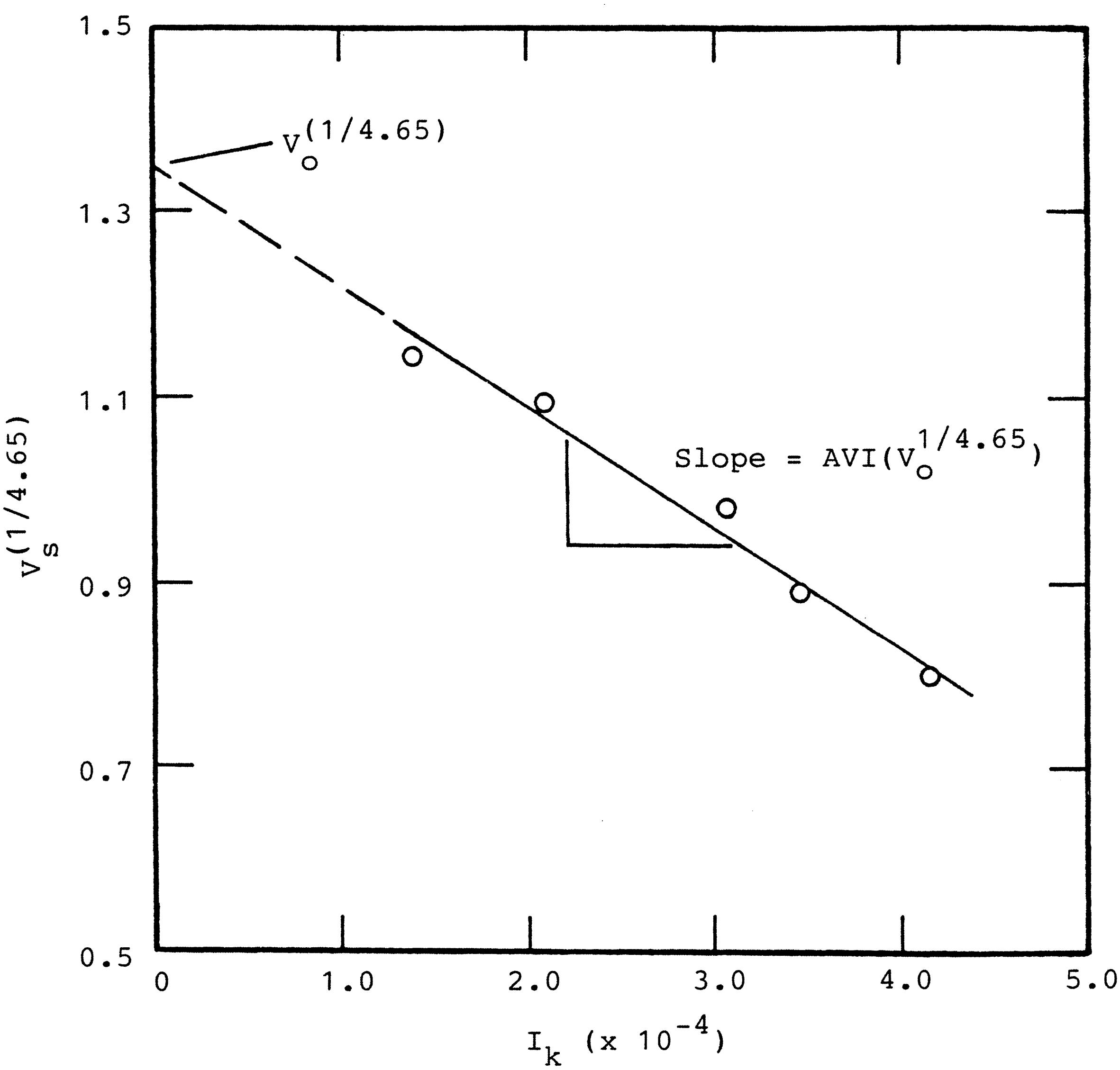

Figure 7: Sample plot of sludge settling velocity versus dry solids volume fraction (I_k) used to determine the AVI values of sludges.

effluent to satisfy instrument particle concentration limits for analysis. Duplicates of each sample were analyzed and the values averaged. A microcomputer was used to determine cumulative particle-size distributions based on particle-volume considerations.

RESULTS AND DISCUSSION

In this chapter, experimental results pertaining to the effects of operating conditions on the thickening and dewatering characteristics of water plant sludges are presented. The effect of operating conditions on sludge floc micro-properties is also presented to facilitate discussion of the sludge thickening and dewatering results. Also, effluent-quality data are shown in order to examine the feasibility of sludge modification through treatment process variation. The majority of the results presented pertain to aluminum hydroxide sludges. However, limited results from ferric hydroxide sludge testing have also been included and discussed to assess whether correlations could be made between the properties of the two sludges.

Sludge Macro-Properties

Sludge Thickening Characteristics

Sludge aggregate-density and size are two parameters cited by other researchers as being important for defining sludge-thickening rates. The thickening data collected during this study are presented in several different ways in order to investigate the effects of operating parameters on these micro-properties and to determine their importance in coagulant sludge thickening. Standard plots of sludge interface settling velocity (V) versus the initial solids concentration (C_0) were used to depict differences in sludge thickening rates due to treatment process variation. Plots of thickening velocity versus floc volume fraction (I_a) have also been included to show the differences in thickening rates caused by aggregate-size differences. Finally, thickening data have been used to derive aggregate densities and aggregate volume index (AVI) values of the sludges tested.

Thickening rates of aluminum hydroxide sludges were found to depend heavily on both coagulation pH and influent turbidity. Data presented in Figures 8 and 9 show that, at a given mass solids concentration, sludge zone-settling velocities increased as coagulation pH decreased. The relationships between sludge-thickening velocity and initial solids concentrations (C_0) for aluminum hydroxide sludges produced when influent turbidities were 0,7, and 50 NTU are displayed in Figures 10 and 11. Sludge-settling rates were vastly improved when sludges were formed by treating 50 NTU turbidity conditions at both pH 7 and pH 8.

Ferric hydroxide sludges thickened similarly to aluminum hydroxide sludges. In addition, they thickened more rapidly when they were formed from waters of higher influent turbidity under lower pH conditions (Figure 12). One possible explanation of these results is that the incorporation of turbidity into the sludge floc causes an

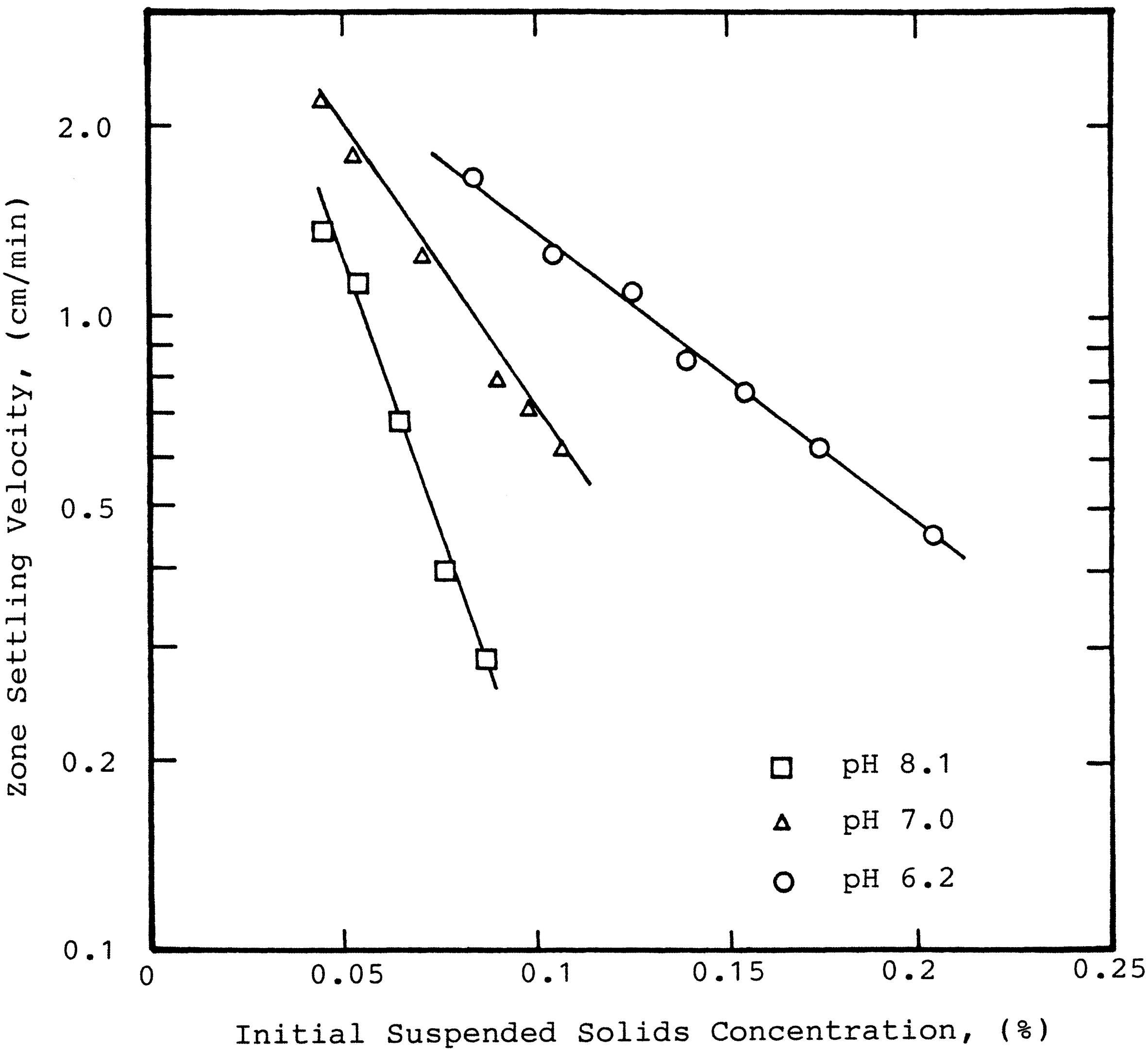

Figure 8: The effect of coagulation pH on the thickening rates of aluminum hydroxide sludges formed under low turbidity conditions.

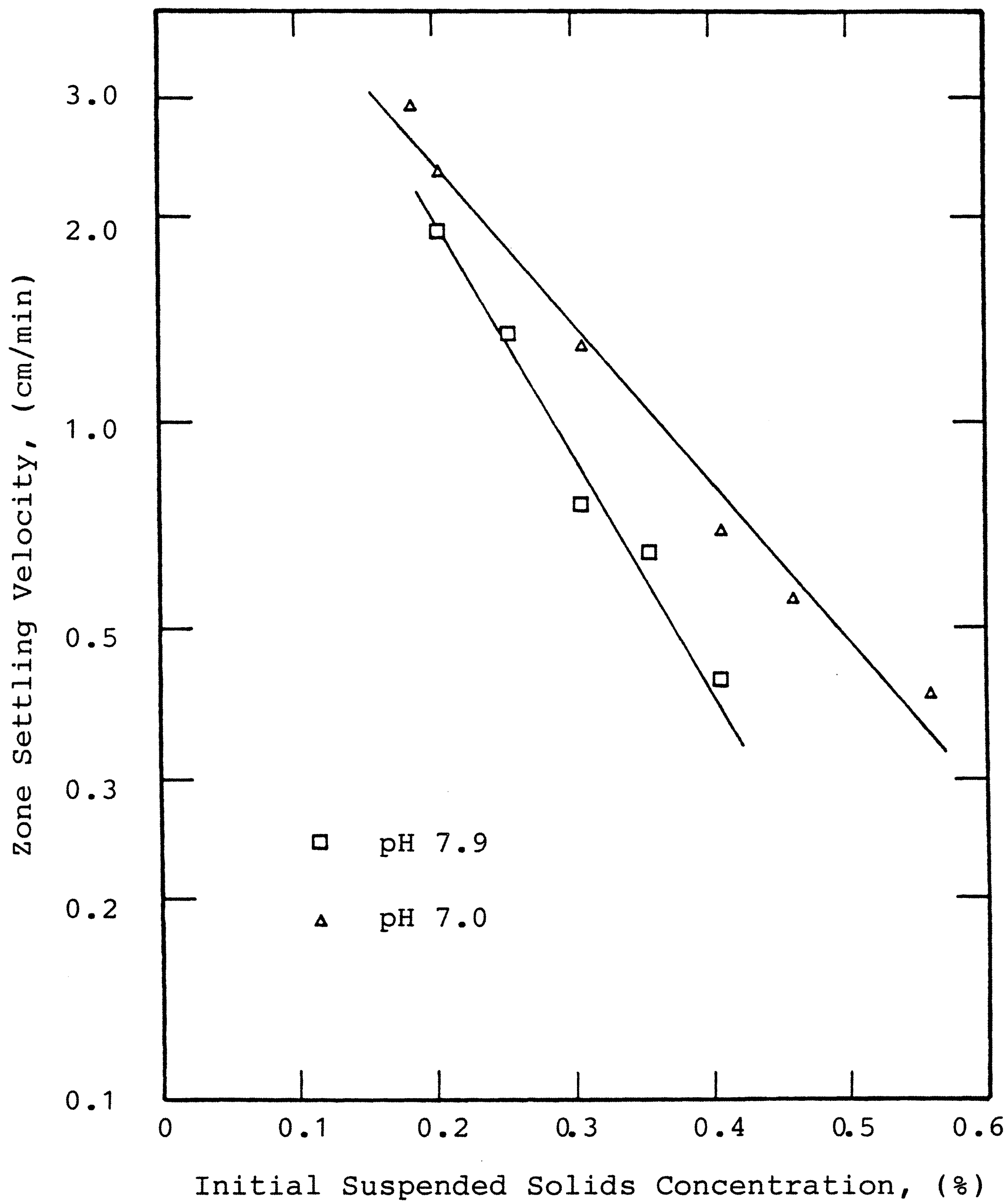

Figure 9: The effect of coagulation pH on the thickening rates of aluminum hydroxide sludges formed under high turbidity conditions.

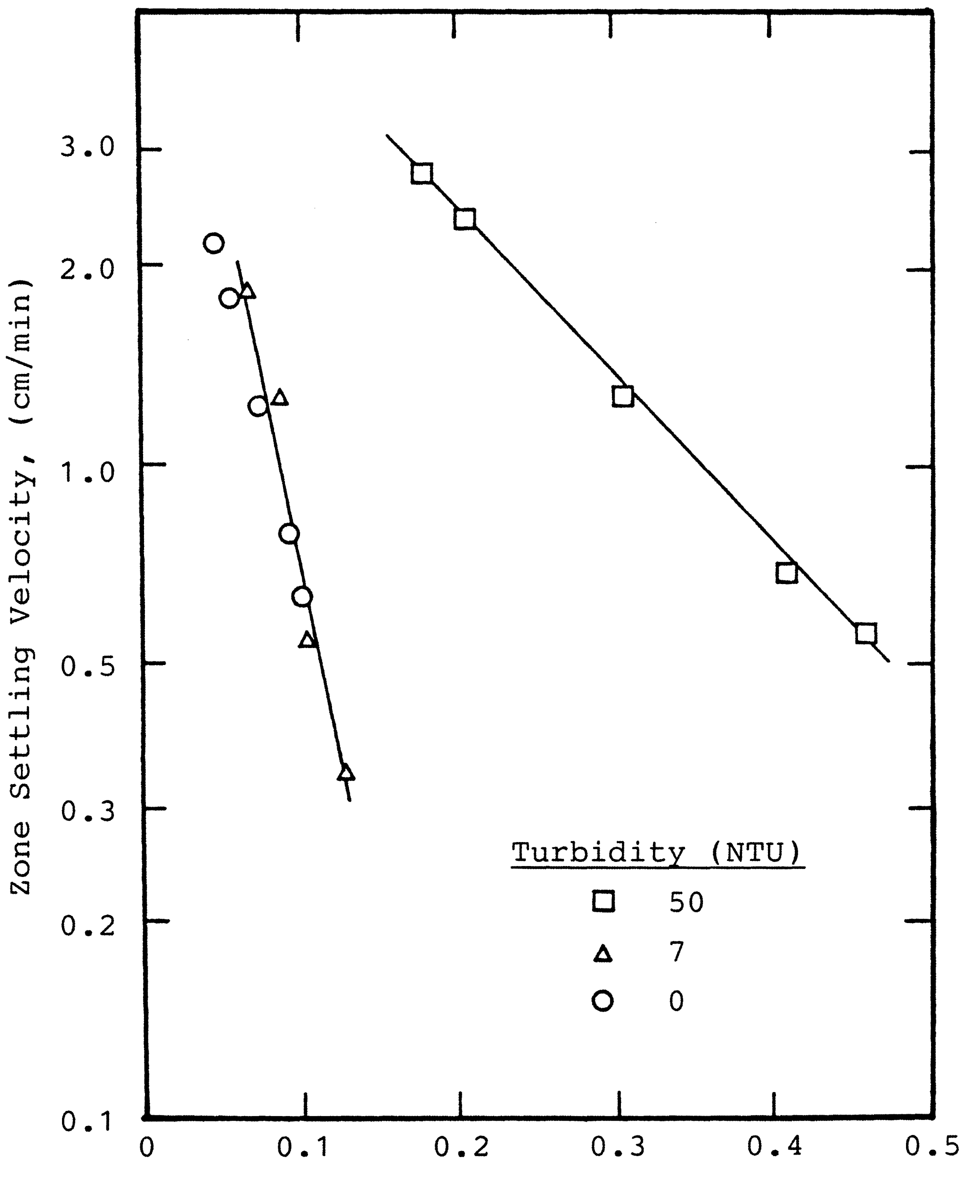

Figure 10: The effect of influent turbidity on the thickening rates of aluminum hydroxide sludges formed at pH 7.

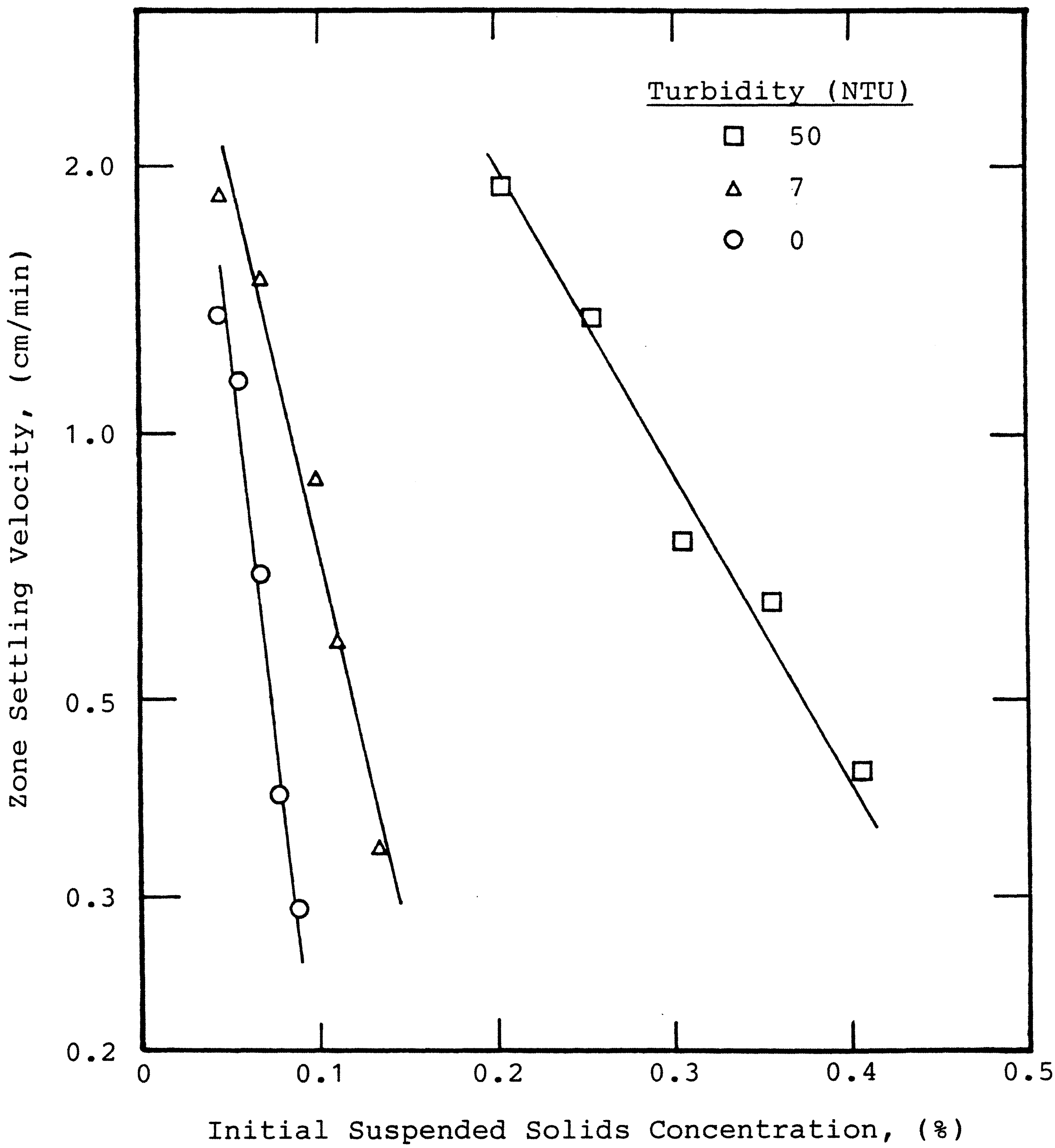

Figure 11: The effect of influent turbidity on the thickening rates of aluminum hydroxide sludges formed at pH 8.

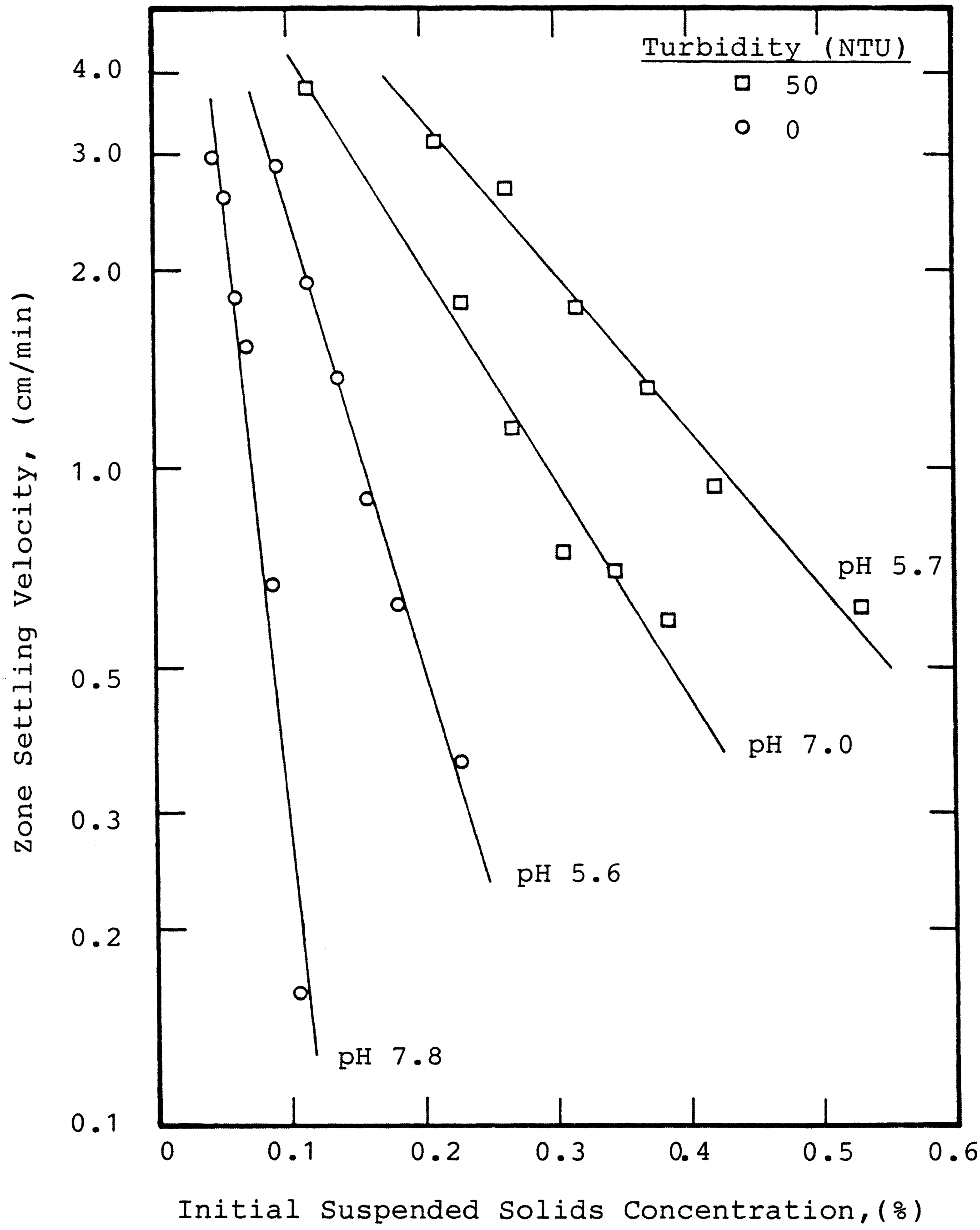

Figure 12: The effect of coagulation pH and influent turbidity on the thickening rates of ferric hydroxide sludges.

increase in floc density and a corresponding improvement in thickening rates. Floc water content data (to be discussed in a subsequent section) support this hypothesis.

The solids concentrations of aluminum hydroxide sludges after 24 hours settling are displayed as a function of both coagulation pH and influent turbidity in Figure 13. Two important trends are evident. First, sludges produced under lower pH conditions settled to greater solids concentrations than those produced under higher pH conditions. Second, aluminum hydroxide sludges produced under conditions of high influent turbidity (50 NTU) settled to higher solids concentrations than those produced under low turbidity (0 or 7 NTU) conditions. The latter was also observed by Calkins and Novak (28) in their study of waste coagulant sludges collected at Missouri water treatment plants.

The settled-solids concentration of a sludge (the extent of thickening) would appear to depend on several sludge micro-properties, including the dry solids density (ρ_k), aggregate density (ρ_a), and compressibility. Because the depth of settled sludge did not exceed 15 cm in any test during this study, compressibility was assumed to have no significant effect on the results. Additionally, the dry densities of sludge solids were unaffected by changes in the coagulation pH, as will be shown in a subsequent section of this thesis.

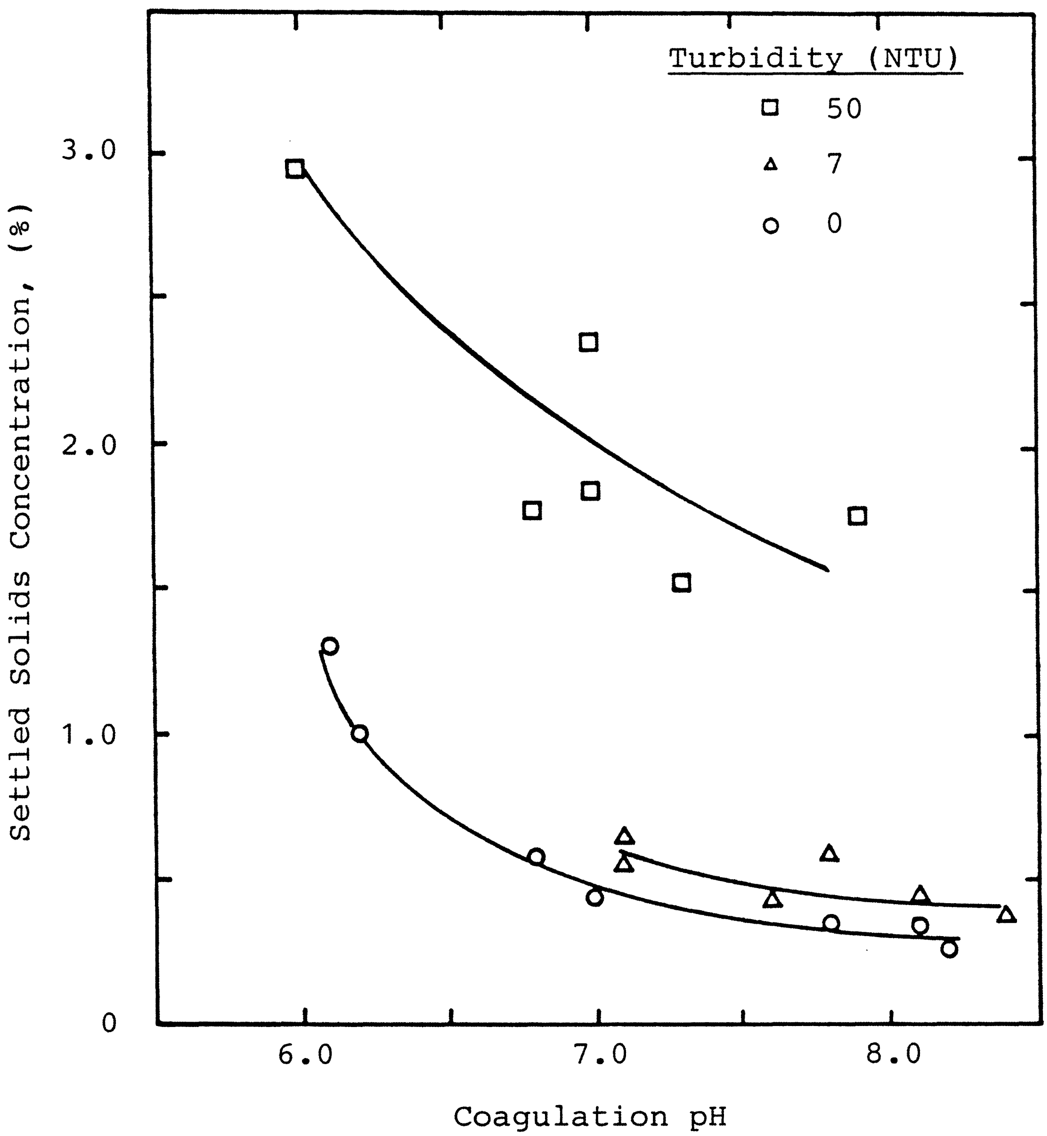

Figure 13: The effects of coagulation pH and influent turbidity on the solids concentrations of aluminum hydroxide sludges obtained following gravity thickening.

Sludge Dewatering Characteristics

Both coagulation pH and influent turbidity significantly affected sludge dewatering characteristics. Figure 14 shows that specific resistance of aluminum hydroxide sludges increased markedly as coagulation pH increased from 6.0 to 8.0. Specific resistance values for sludges formed under high turbidity conditions were much smaller than those formed under low-turbidity conditions. Dewatering rates of sludges formed under high turbidity conditions also were less dependent on coagulation pH.

The specific resistance values of ferric hydroxide sludges decreased with decreased pH or increased influent turbidity (Figure 15), as did the resistance values of aluminum hydroxide sludges. However, due to the small data base used for Figure 15, less emphasis should be placed on the variability of the effect of coagulation pH on specific resistance with respect to turbidity.

The cake solids concentration obtained by vacuum dewatering was also affected by treatment process variations. Aluminum hydroxide sludges produced under conditions of high turbidity dewatered to at least twice the solids concentration that the low turbidity sludges did (Figure 16). Also, final cake solids concentrations increased as coagulation pH was reduced from pH 8.0 to pH 6.0.

Figure 17 shows similar results obtained for ferric

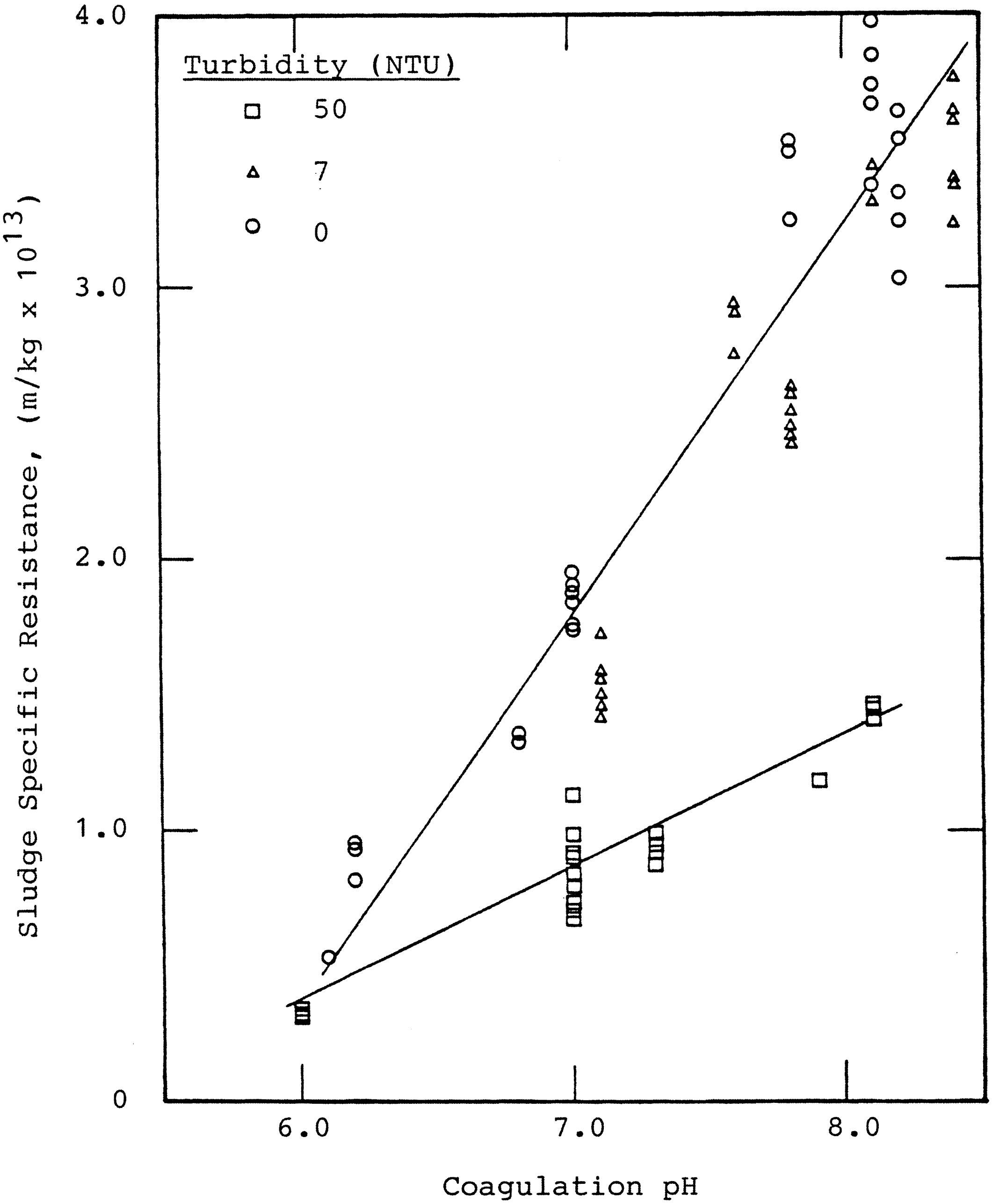

Figure 14: Variations in the specific resistance values of aluminum hydroxide sludges as a function of coagulation pH and influent turbidity.

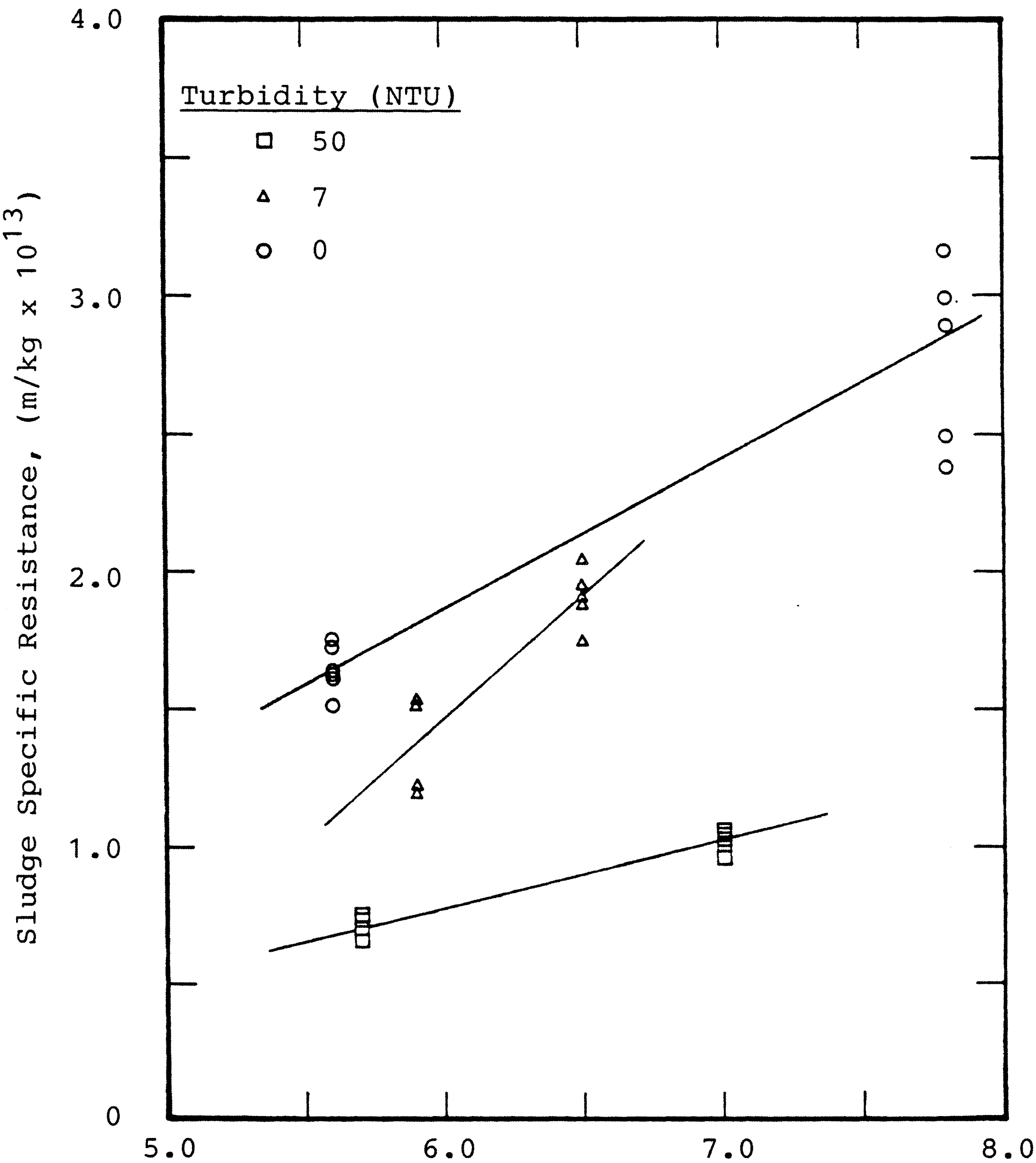

Figure 15: The effects of coagulation pH and influent turbidity on the specific resistance values of ferric hydroxide sludges.

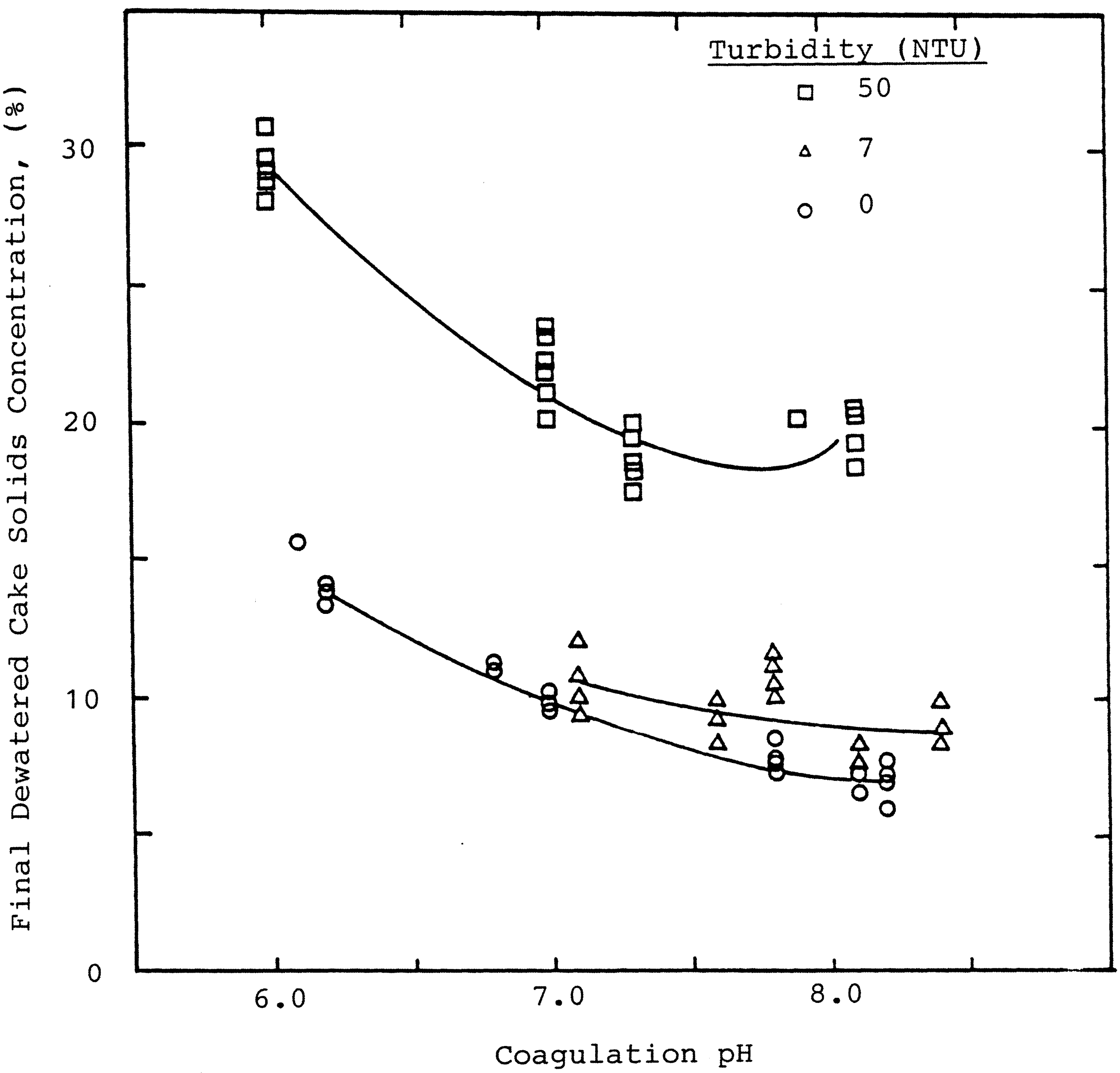

Figure 16: Differences in the final dewatered cake solids concentrations of aluminum hydroxide sludges as a function of coagulation pH and influent turbidity.

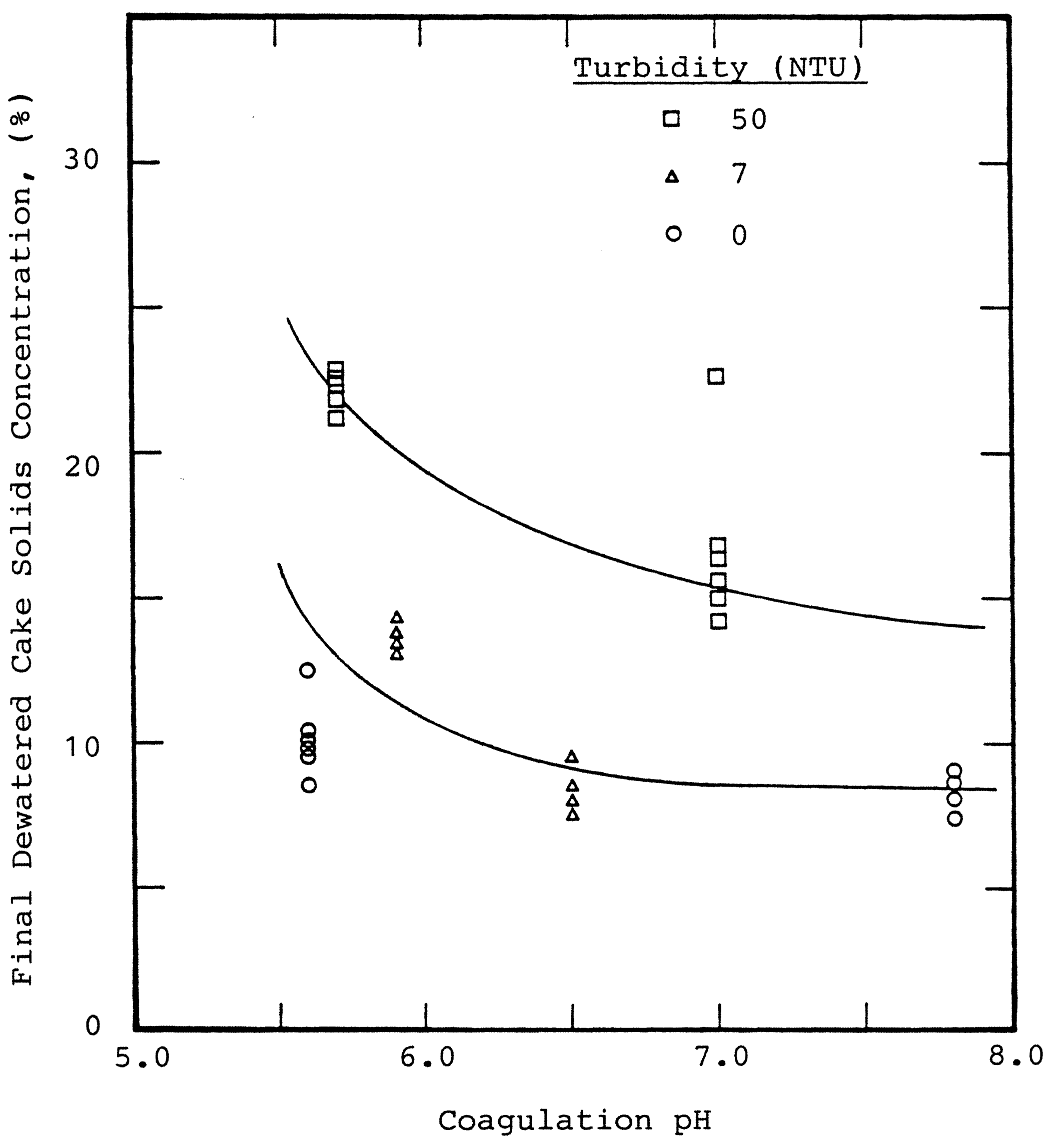

Figure 17: The effects of coagulation pH and influent turbidity on the final dewatered cake solids concentrations of ferric hydroxide sludges.

hydroxide sludges. However, at comparable pH values, ferric hydroxide sludges did not dewater to the extent the aluminum hydroxide sludges did. Also, ferric hydroxide sludges formed in high-turbidity waters dewatered to final cake solids concentrations approximately 50 percent higher than those for low turbidity sludges. These results suggest that both ferric and aluminum hydroxide sludges produced under high pH conditions contain more internal floc water, water that is not removed by conventional mechanical dewatering methods.

A comparison between the final cake solids concentrations for ferric and aluminum hydroxide sludges with respect to settled solids concentration is depicted in Figure 18. On an equivalent settled-solids basis, aluminum hydroxide sludges consistently dewatered to higher solids concentrations than did ferric hydroxide sludges. Another important conclusion to be drawn from these data is that the dewatered cake-solids concentrations of both ferric and aluminum hydroxide sludges can be predicted from settled solids data.

The effect of the alum dose/initial turbidity ratio on sludge macro-properties should also be noted. Table 1 shows the increase in specific resistance and the decrease in settled solids and final dewatered cake solids concentrations that occurred as the alum/turbidity ratio increased. These variations will be discussed later with respect to changes in

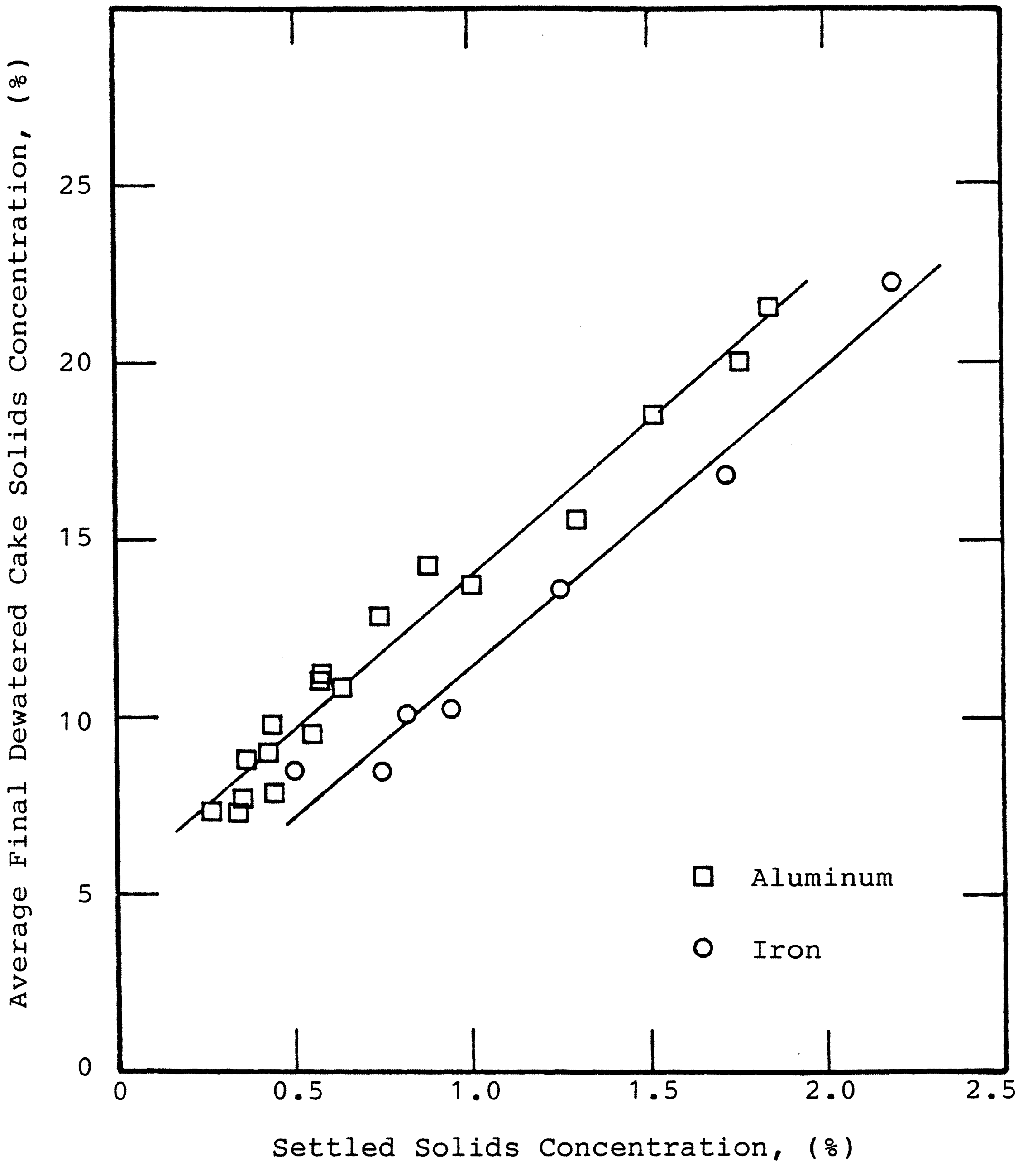

Figure 18: Relationship between settled and final dewatered cake solids concentrations for both aluminum and ferric hydroxide sludges.

Table 1. Variations in aluminum hydroxide sludge macro-properties as a function of the alum dose/initial turbidity ratio (pH = 6.8 - 7.1).

Alum Dose/ Inf. Turbidity Ratio	Settled Solids Conc.(%)	Specific Resistance (m/kg x 10^{13}) Ave.	Range	Dewatered Cake Solids Conc.(%)
1.6	1.84	0.91	0.79-1.12	21.6
3.6	0.88	1.16	1.09-1.20	14.3
11.4	0.55	1.52	1.30-1.72	10.1
	0.43	1.85	1.75-1.95	9.8

floc water content or floc density.

Sludge Floc Micro-Properties

Dry Solids Density (ρ_k)

The dry density of the solids composing a sludge is important because it, along with water content, has a role in determining the density of sludge aggregates. Results of this study show that coagulation pH does not affect ρ_k (Table 2). On the other hand, the dry solids density decreased with the incorporation of turbidity (kaolin) into the sludge. This would suggest that kaolin is less dense than either dry aluminum hydroxide or ferric hydroxide solids.

Compressibility

Compressibility is a measure of the extent to which the basic sludge structure deforms during the application of an external force. This process is an important parameter in dewatering and can have both positive and negative effects. For example, sludge at the bottom of a lagoon or in a centrifuge may be compacted, thus increasing the suspended solids concentration. However, compression of sludge during vacuum dewatering reduces sludge cake porosity, thereby decreasing the dewatering rate.

Experimental results displayed in Figure 19 indicate that sludge compressibility did not change with either coagulation pH or influent turbidity. Coefficients of

Table 2. The effect of influent turbidity on the dry solids density (ρ_k) of aluminum and ferric hydroxide sludges formed at pH 7.0.

Coagulant	Turbidity (NTU)	Ave. ρ_k (g/L)
alum	0	3170
alum	50	2760
$FeCl_3$	0	3790
$FeCl_3$	50	2830

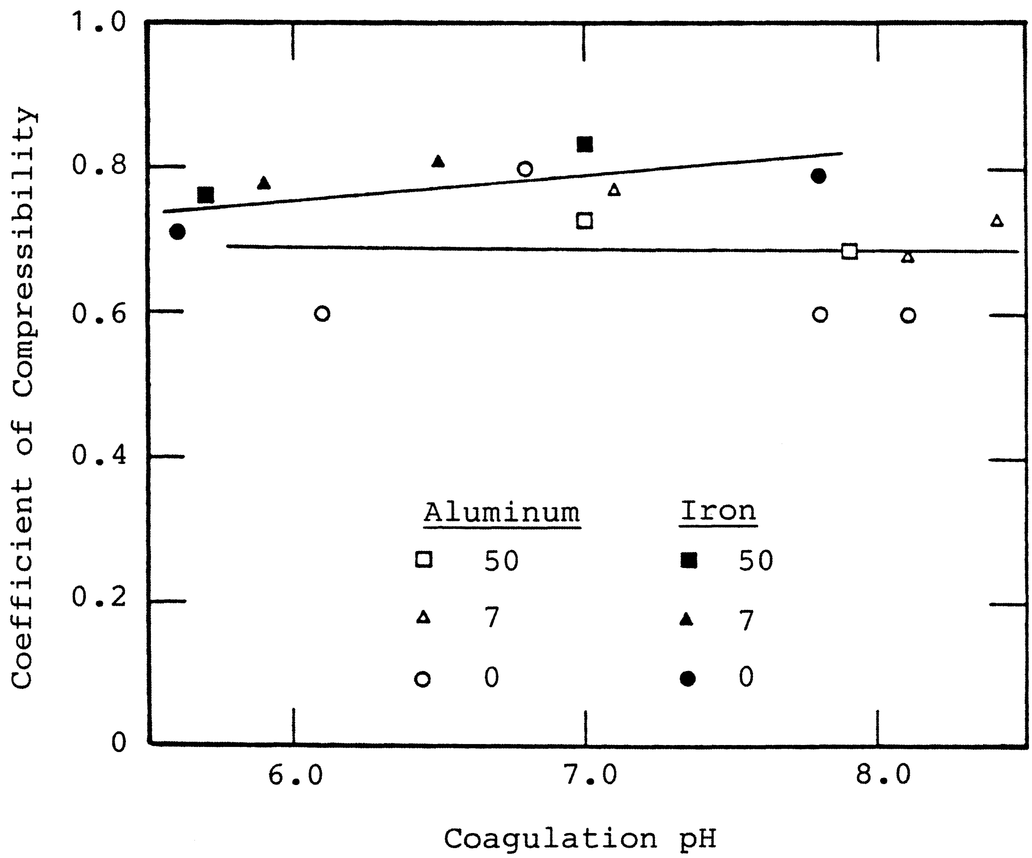

Figure 19: The effect of coagulation pH and influent turbidity on the compressibility of aluminum and ferric hydroxide sludges.

compressibility varied randomly from 0.6 to 0.8 for aluminum hydroxide sludges and from 0.71 to 0.83 for ferric hydroxide sludges. In comparison to other reported compressibility data (42) these values should be interpreted to mean that the sludges produced and tested during this study were not highly compressible.

Particle-Size Distribution

This section presents the results of size-distribution analyses of suspensions removed from the pilot-plant after flocculation. Though not meant to perfectly imitate the size distributions found during sludge settling, thickening, or dewatering, these data should indicate trends that would be applicable to those three processes. No attempt was made to determine the size distribution during thickening and dewatering, as differences in the aggregate shear associated with these processes would be impossible to duplicate.

The effects of influent turbidity on the size distribution of aluminum hydroxide aggregates are depicted in Figures 20-22 for pH 6.1, 6.8, and 8.1, respectively. Generally, larger particles were produced when coagulating in the absence of turbidity, than when the influent turbidity was 50 NTU. However, a decrease of the fraction of the smallest particles occurred under conditions of high turbidity as pH increased from 6.1 to 8.1 (Figures 20-22). These fine particles were thought to have caused a

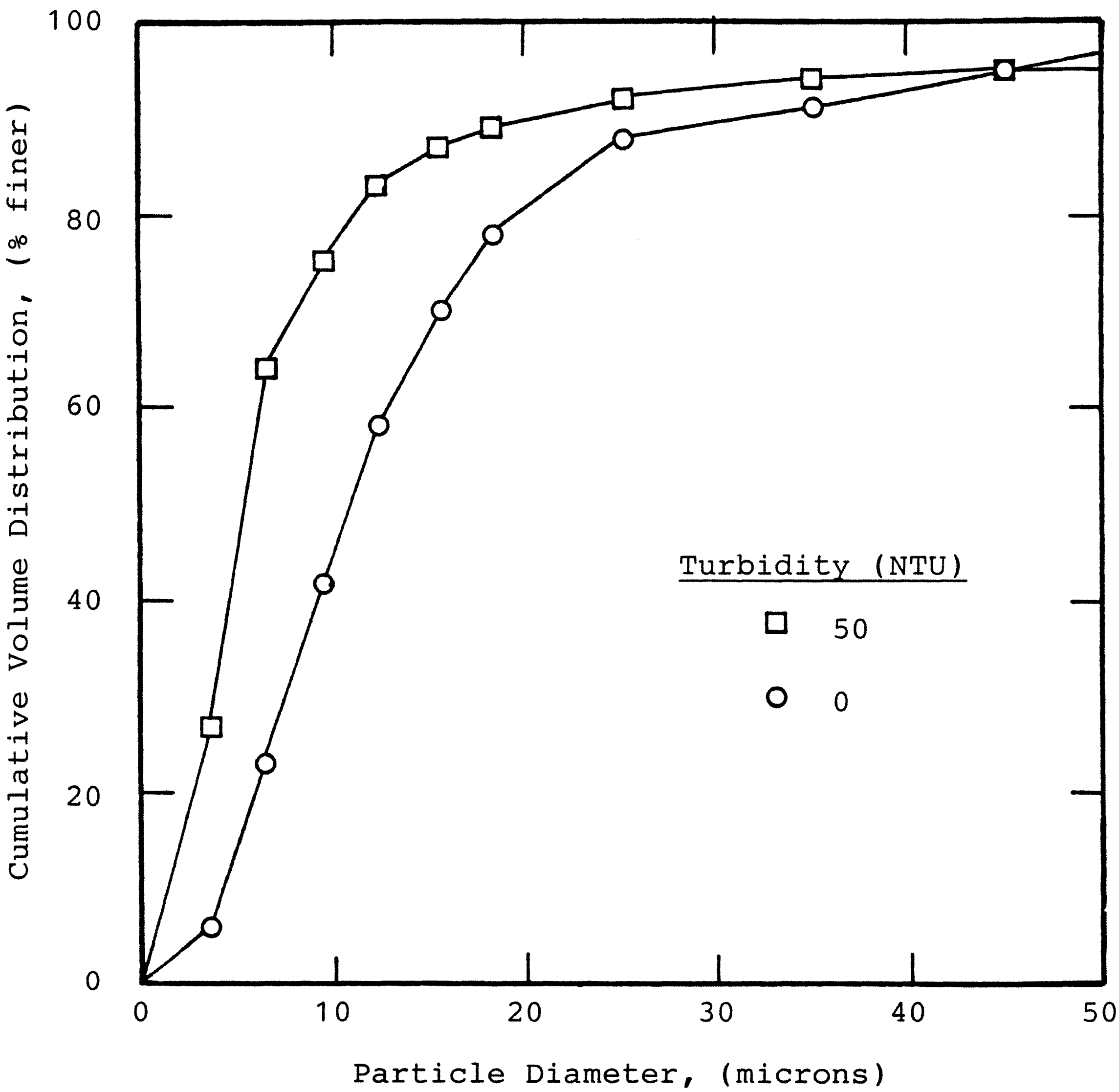

Figure 20: The effect of influent turbidity on the size distribution of aluminum hydroxide floc formed at pH 6.

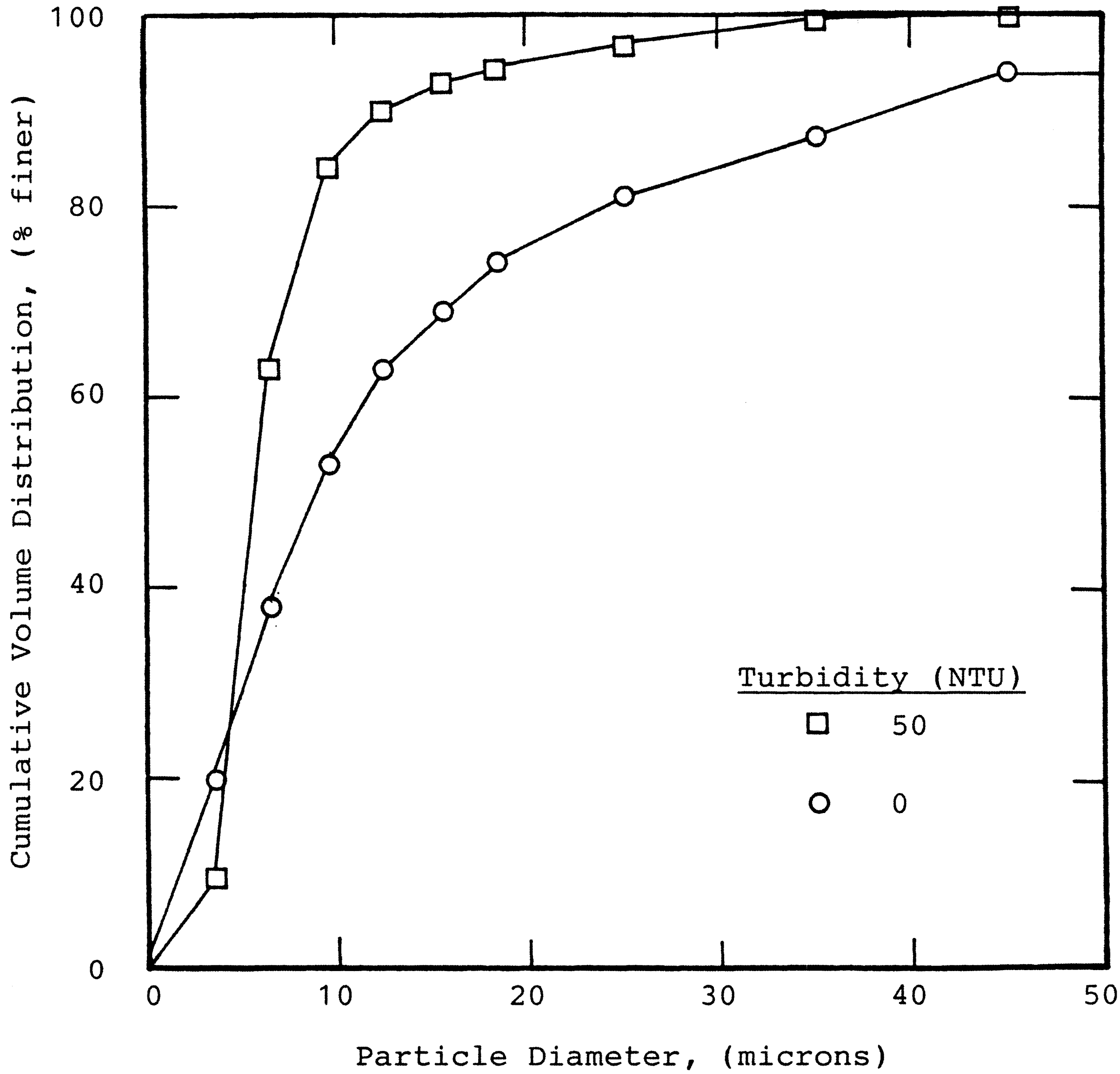

Figure 21: The effect of influent turbidity on the size distribution of aluminum hydroxide floc formed at pH 6.8.

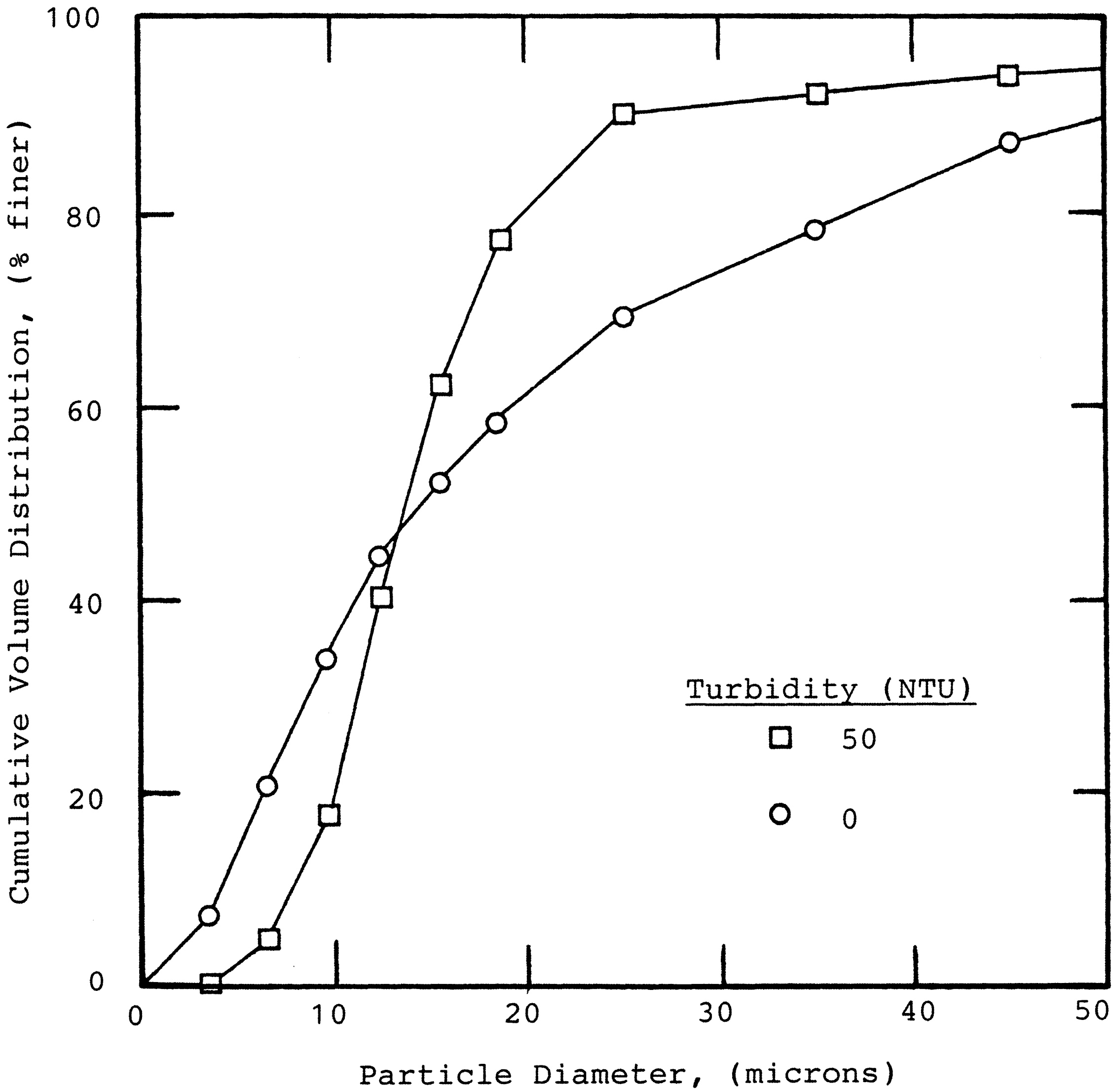

Figure 22: The effect of influent turbidity on the size distribution of aluminum hydroxide floc formed at pH 8.1.

significant portion of the effluent turbidity. Data indicated a significant increase in effluent turbidity when treating the higher kaolin content waters; turbidity also increased as coagulation pH decreased.

The effects of coagulation pH on the particle-size distribution are shown in Figures 23 and 24 for sludge flocs formed under low and high turbidity conditions, respectively. For both turbidity conditions, aluminum hydroxide aggregates formed at pH 8.1 were somewhat larger than those formed at either pH 6.2 or 6.8. Differences between the size distributions at pH 6.2 and pH 6.8 appear to be insignificant.

Figures 25 and 26 show the effect of turbidity on the size distributions of ferric hydroxide floc at pH 5.6 and 7.0, respectively. Smaller floc were formed in high-turbidity waters than in low-turbidity waters at pH 7.0. However, at pH 5.6, the opposite was true. One possible reason for this is a change in coagulation mechanism from "sweep floc" to charge neutralization as the pH decreased. The ferric chloride stability-coagulation diagram (Figure 2) proposed by Johnson and Amirtharajah (5) supports this theory.

The effect of coagulation pH on the size of ferric hydroxide aggregates is shown in Figures 27 and 28. In the absence of turbidity, ferric hydroxide aggregate sizes

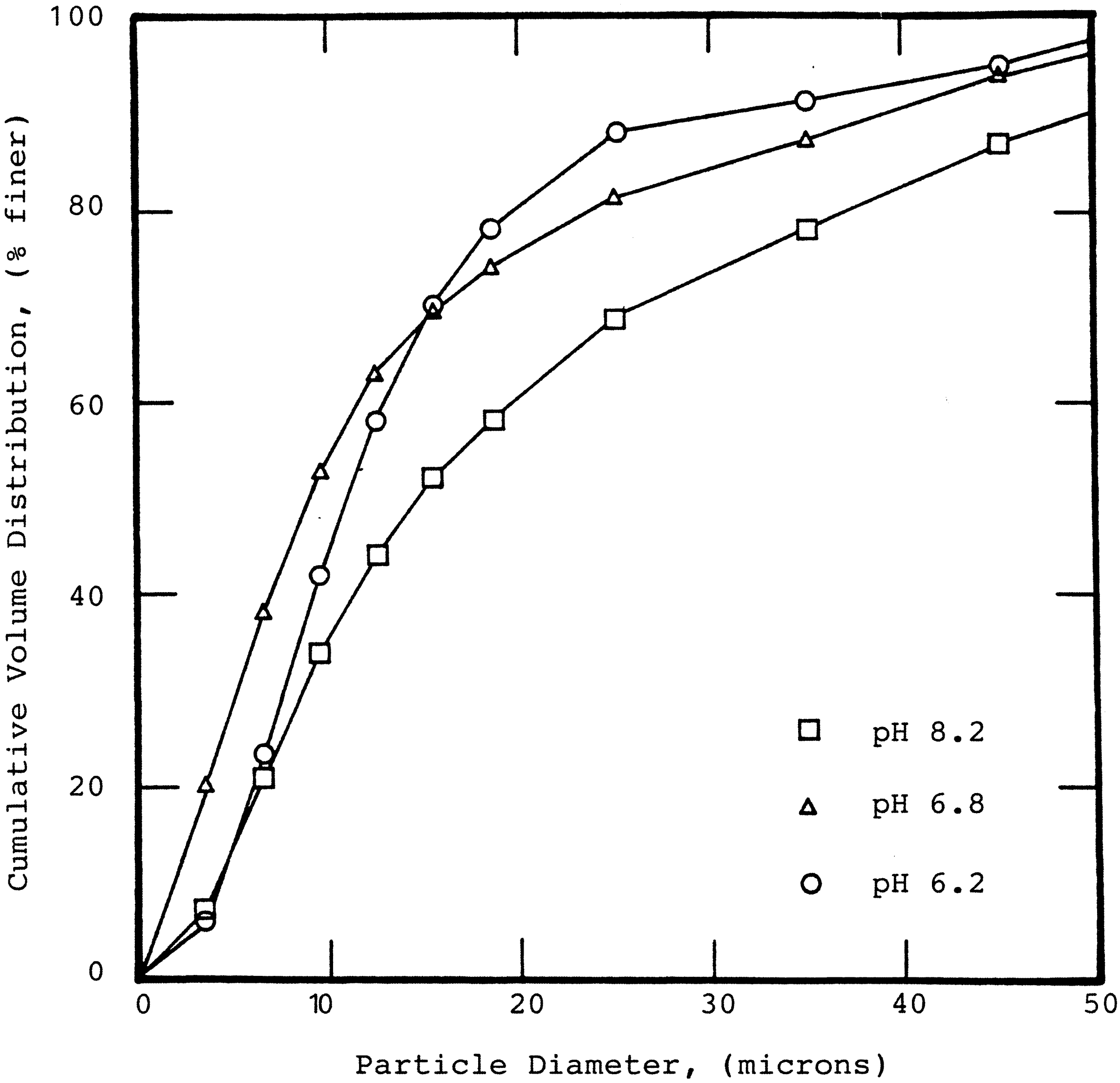

Figure 23: The effect of coagulation pH on the size distribution of aluminum hydroxide floc formed under low turbidity conditions.

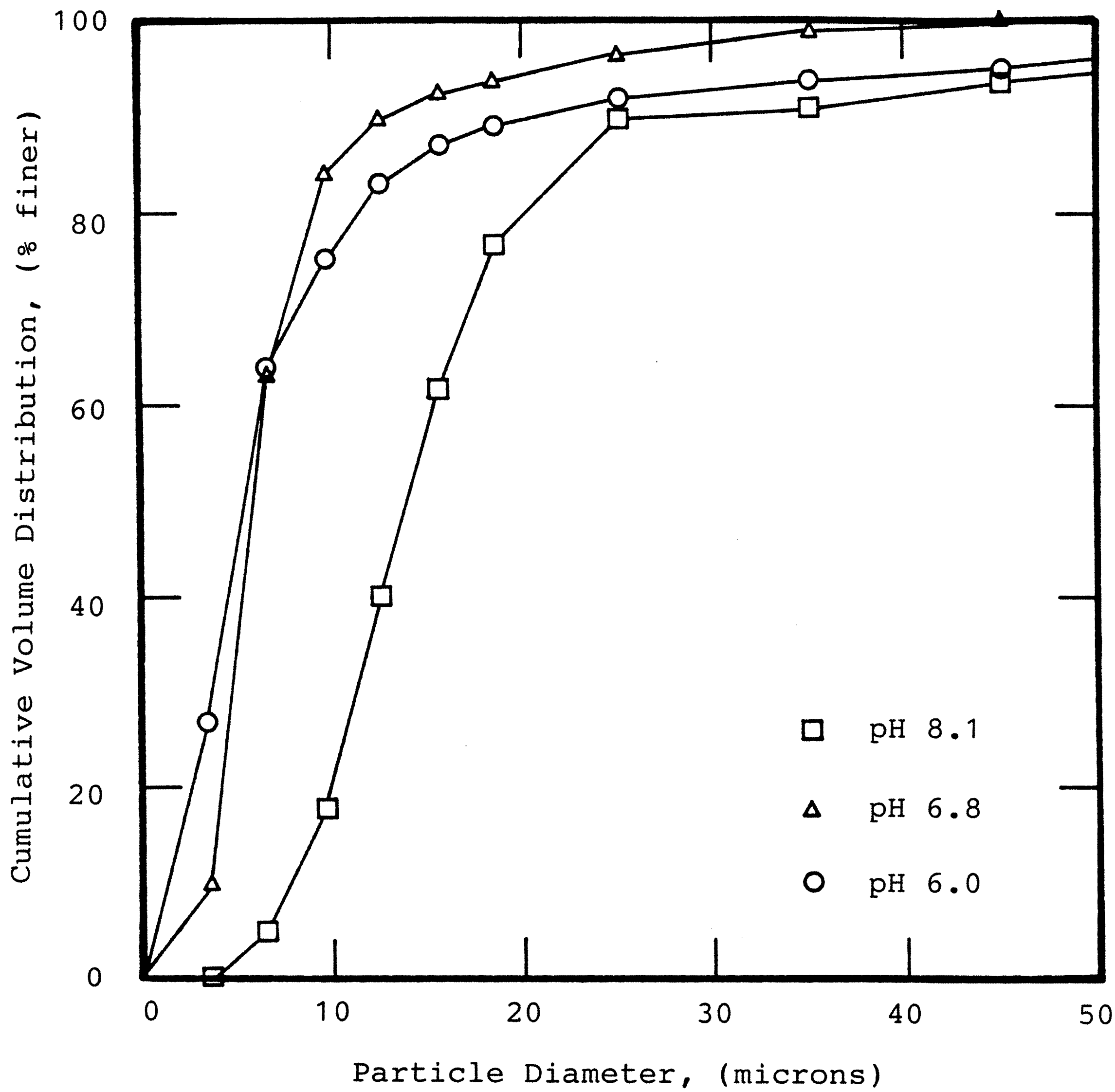

Figure 24: The effect of coagulation pH on the size distribution of aluminum hydroxide floc formed under high turbidity conditions.

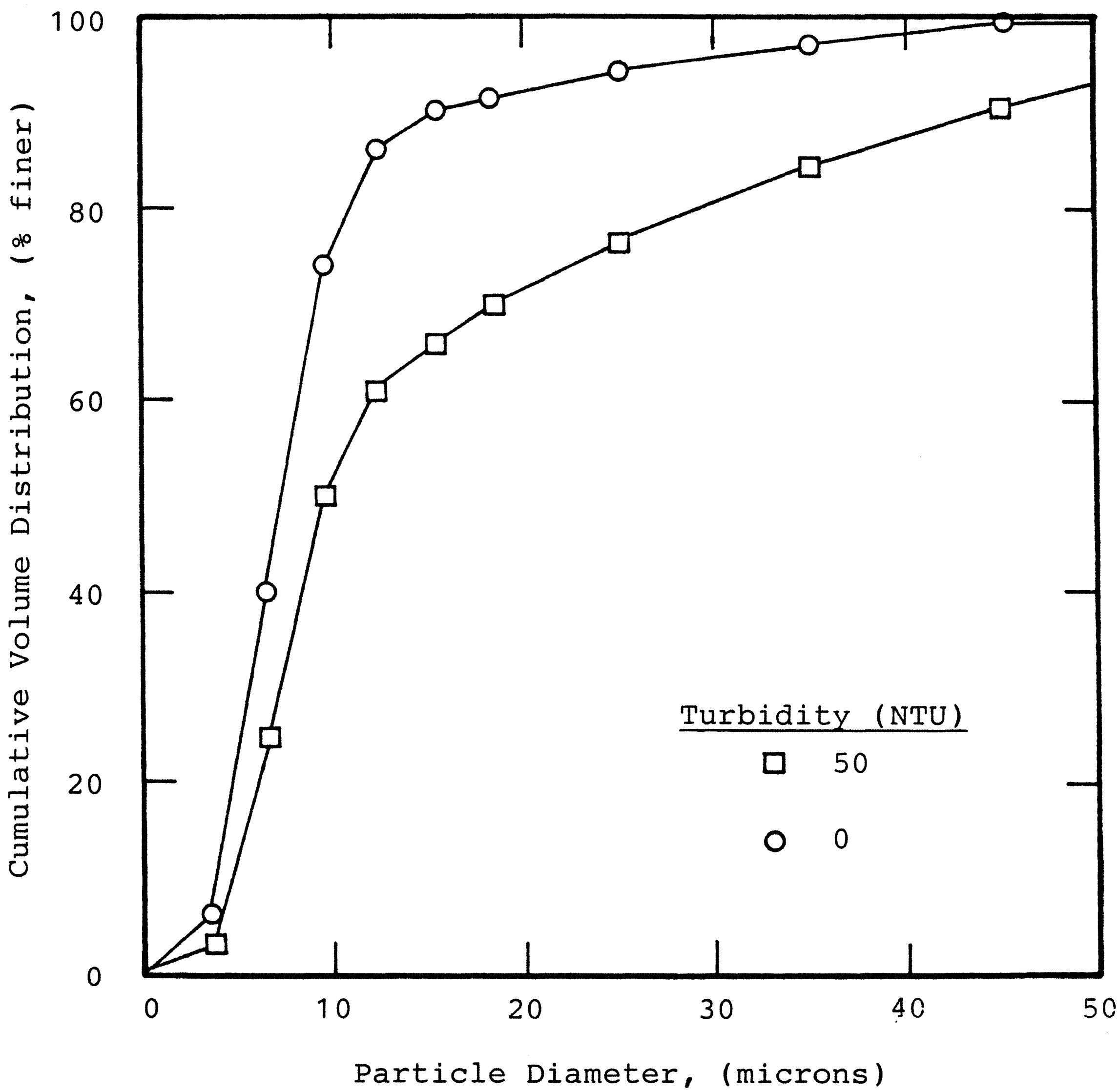

Figure 25: The effect of influent turbidity on the size distribution of ferric hydroxide floc formed at pH 5.6.

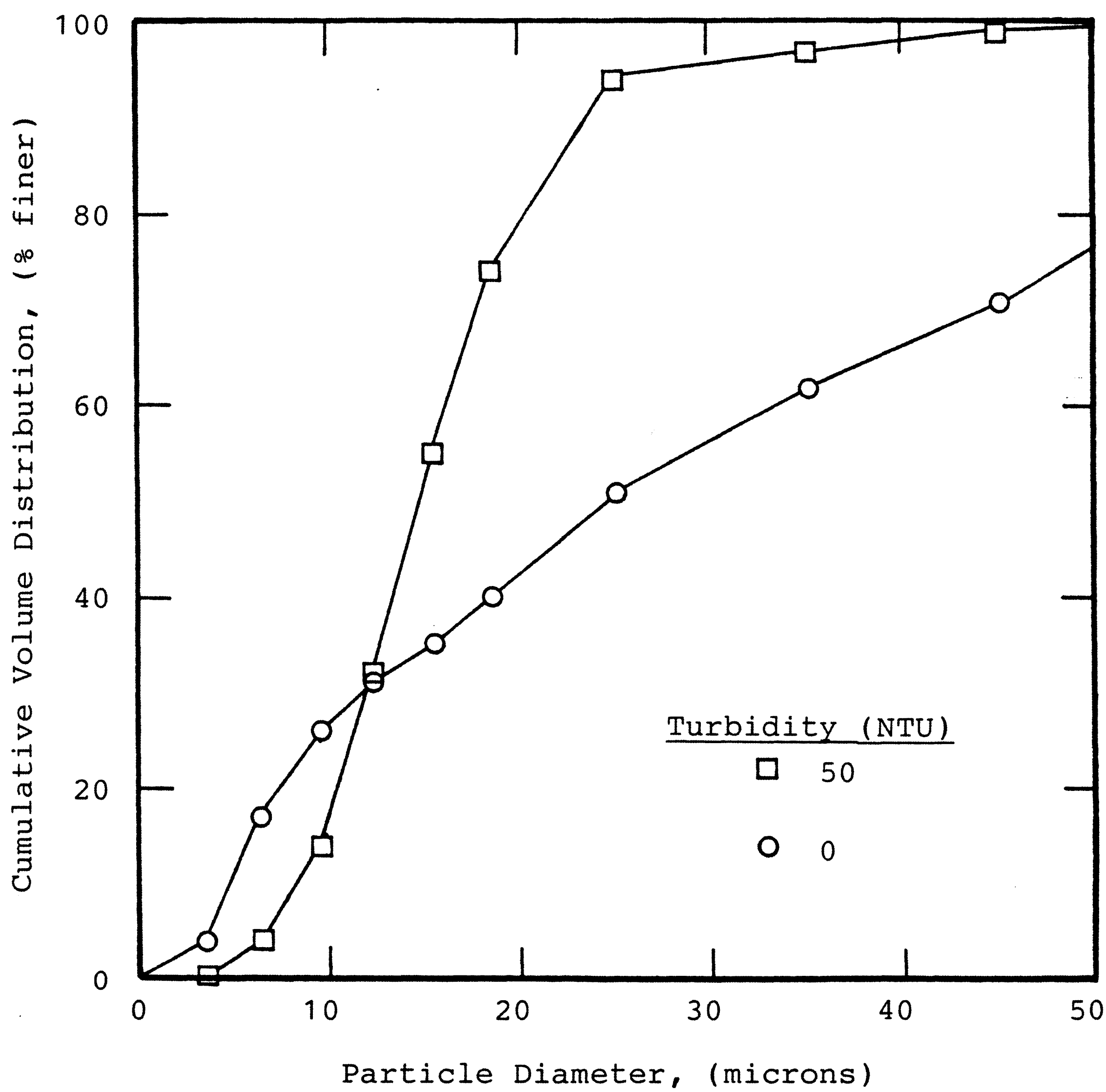

Figure 26: The effect of influent turbidity on the size distribution of ferric hydroxide floc formed at pH 7.0.

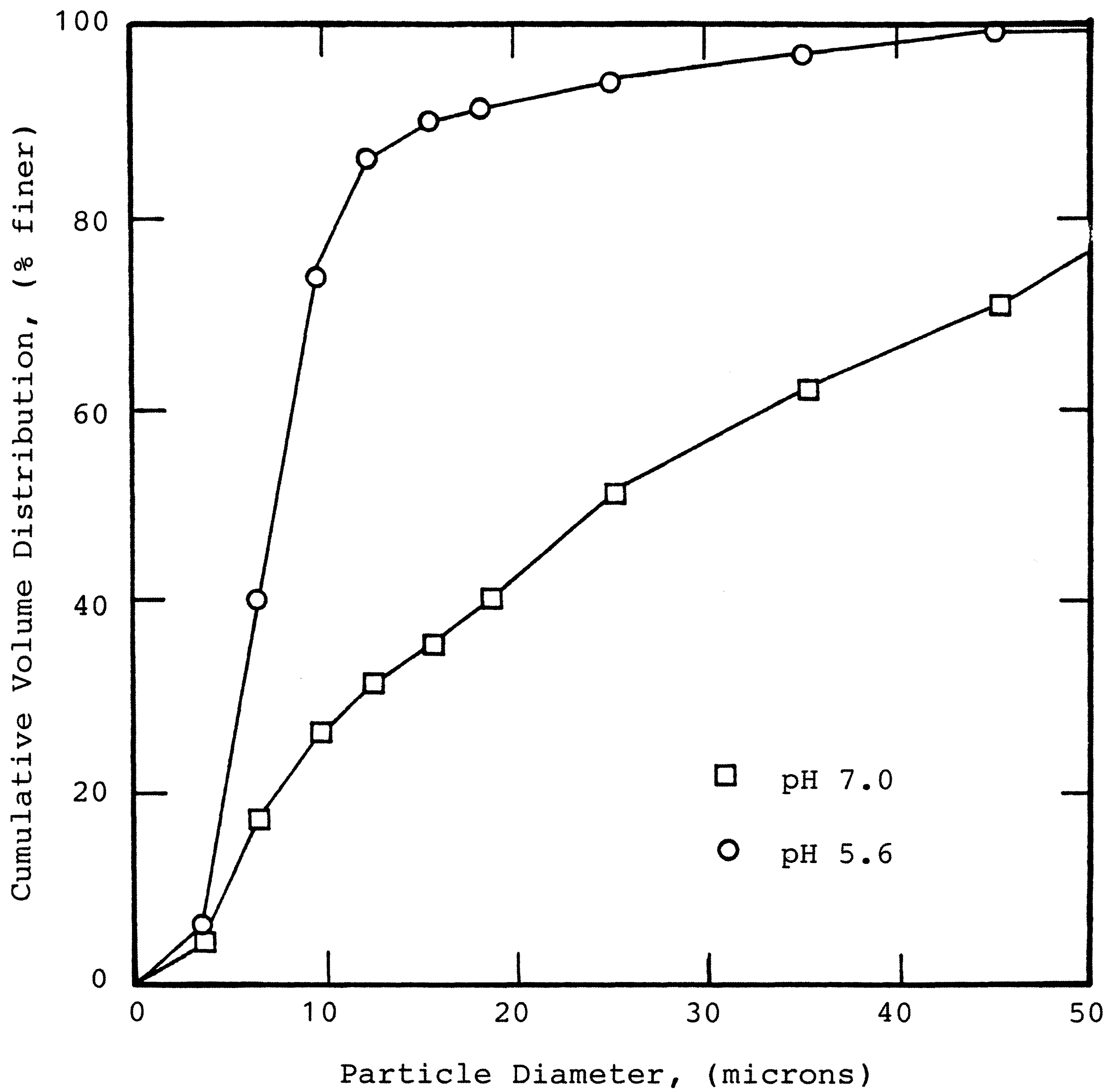

Figure 27: The effect of coagulation pH on the size distribution of ferric hydroxide floc formed under low turbidity conditions.

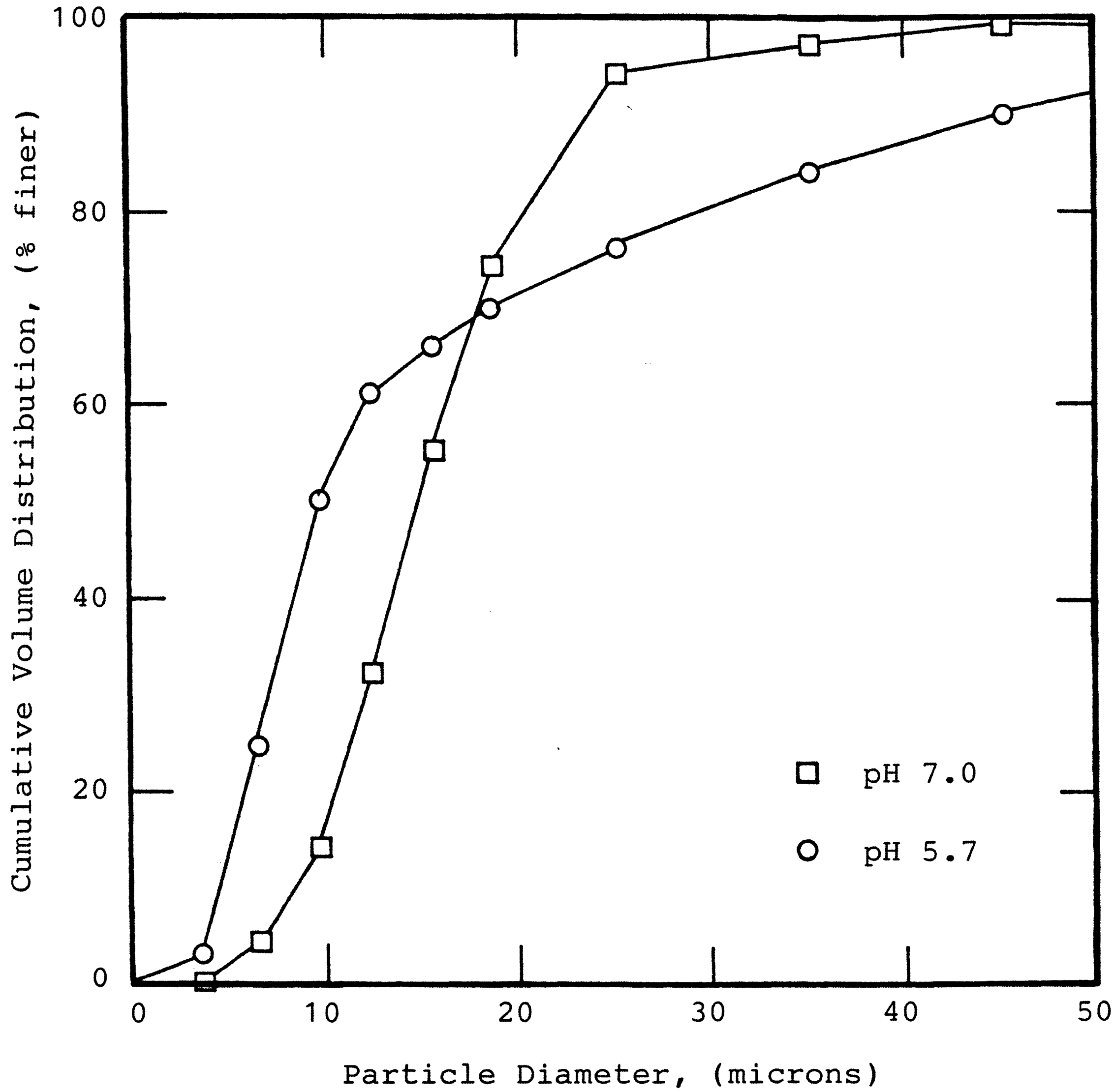

Figure 28: The effect of coagulation pH on the size distribution of ferric hydroxide floc formed under high turbidity conditions.

increased drastically as the pH increased from 5.6 to 7.0 (Figure 27). Similar findings were reported by Ham and Christman (16), who found ferric hydroxide floc to be both larger and stronger than aluminum hydroxide floc. Figure 28 displays a reduction in the effect of coagulation pH in the presence of high turbidity.

Aggregate Density (ρ_a)

The aggregate densities of aluminum and ferric hydroxide sludges were estimated from thickening data by methods descibed in the Literature Review. Direct measurements of aggregate densities could not be made because accurate techniques do not exist. Shown in Table 3 are the aggregate densities and aggregate volume indeces (AVI) obtained of sludges produced during this study. Sludge aggregate densities increased both as coagulation pH decreased from 8.0 to 6.0 and as influent turbidity levels increased from 0 to 50 NTU. Increases in ρ_a correlated extremely well with increases in 1) settled solids concentration, 2) final dewatered solids concentration, 3) thickening rates, and 4) dewatering rates.

The AVI is defined as the ratio of aggregate volume to dry solids volume. The higher the AVI, the higher the aggregate water content. From the data in Table 3, ferric hydroxide sludges appeared to incorporate more water into the aggregate structure than aluminum hydroxide sludges formed

Table 3. The effect of coagulation pH and influent turbidity on the aggregate densities (ρ_a) and AVI values of aluminum and ferric hydroxide sludges.

		ρ_a (g/cm^3)		AVI	
Coagulant	pH	(0 NTU)	(50 NTU)	(0 NTU)	(50 NTU)
	8.0	1.001	1.006	1630	350
alum	7.0	1.002	1.007	1060	200
	6.2	1.005	-	570	-
	7.8	1.001	-	1830	-
$FeCl_3$	7.0	-	1.006	-	320
	5.6	1.004	1.008	930	230

under similar pH conditions. Also, the addition of turbidity to the sludge both reduced the aggregate water content and decreased the effect of pH on water content. Thus it seems that the water content of hydroxide sludges would be reduced when waters of high influent turbidity are treated. Also, water content should be decreased by reducing the coagulation pH.

Plots of sludge settling velocity versus the aggregate volume fraction (I_a) have been presented (Figures 29,30) in order to obtain further insight into roles of ρ_a and aggregate size in the thickening process. Although these plots do not entirely eliminate the effect of aggregate density differences, they remove the extreme density bias found in plots of sludge settling velocity versus initial mass solids concentration.

Two important trends are displayed in Figure 29. First, among those sludges produced under equal influent turbidity conditions, those formed at low pH (higher density sludges) thickened more slowly than the low density sludges formed at high pH. This suggests either a decrease in aggregate size or an increase in aggregate stability as pH decreased from 8.0 to 6.0. Particle-size distributions presented previously show decreases in floc size as pH decreased from 8.0 to 7.0. However, the significant difference in thickening rates between sludges formed at pH 6.2 and 7.0 is not supported by

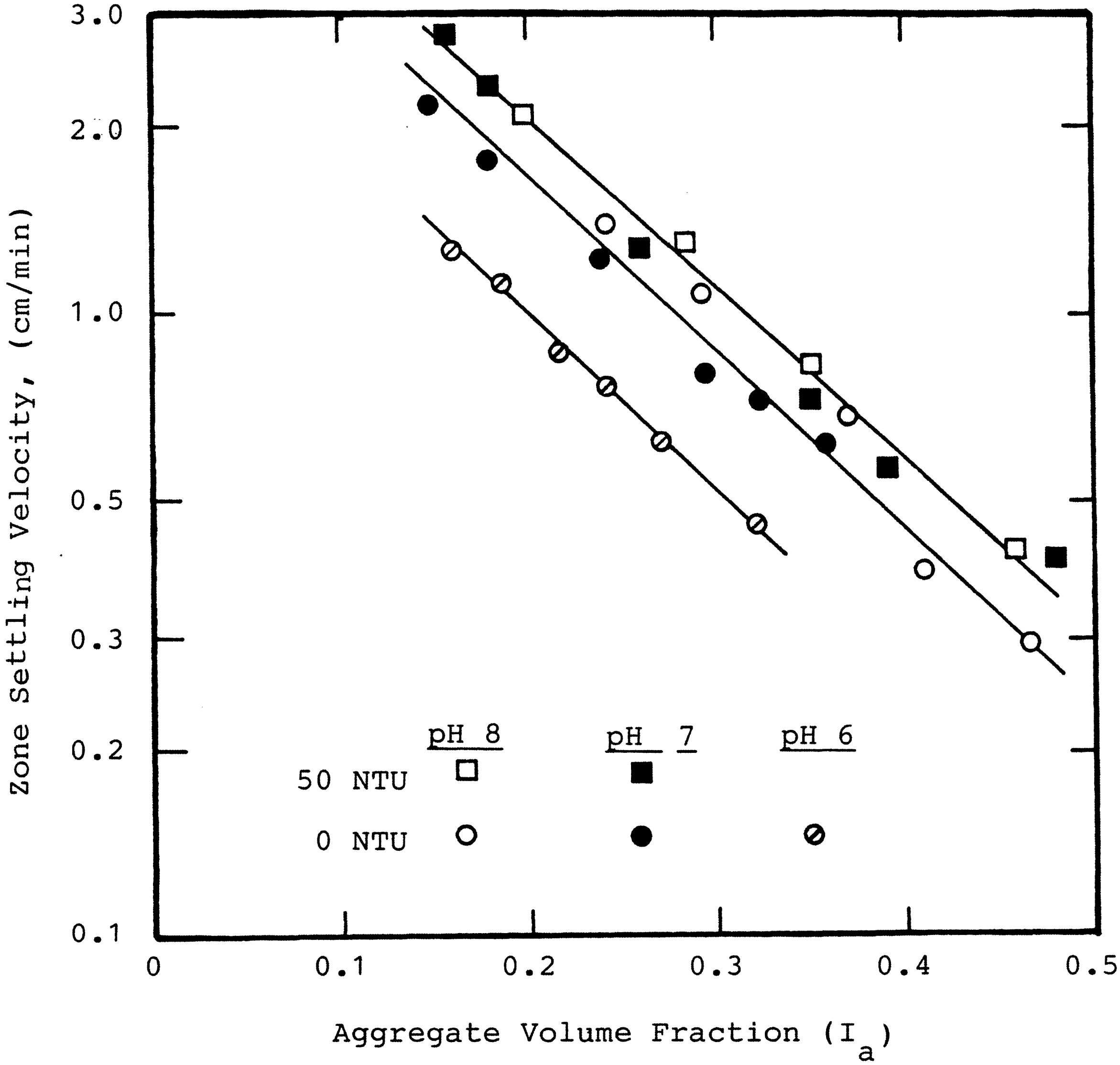

Figure 29: The effect of coagulation pH and influent turbidity on the thickening rates of aluminum hydroxide sludges.

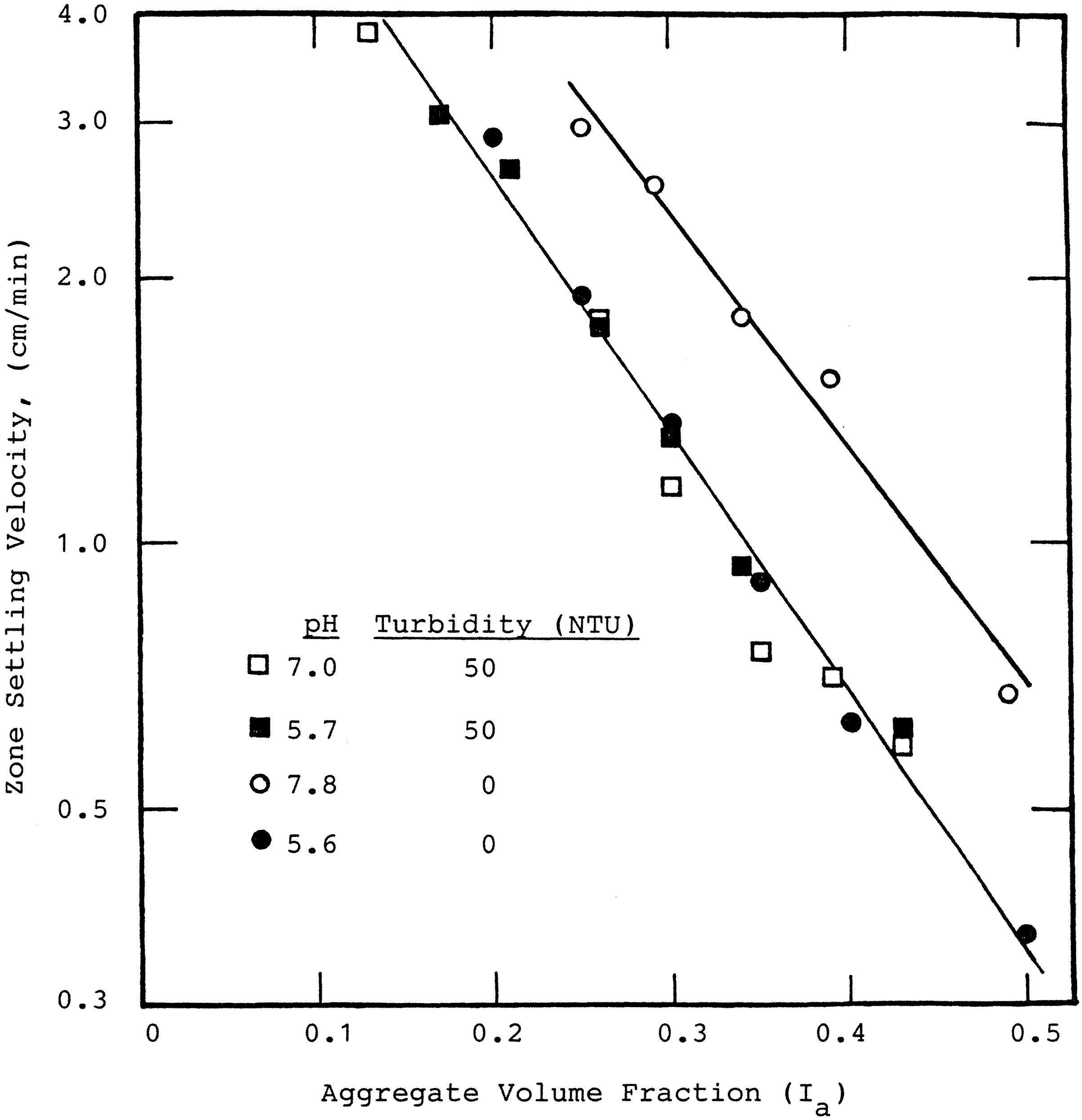

Figure 30: The effect of coagulation pH and influent turbidity on the thickening rates of ferric hydroxide sludges.

size considerations since the floc-size distribution was similar at these two pH values.

Second, higher density sludges produced under high turbidity conditions thickened more rapidly than low density sludges produced in the absence of turbidity. Particle-size distributions were similar for sludges produced under low and high turbidity conditions; therefore, the rapid thickening rates of high turbidity sludges (Figure 29) were probably due to an increase in floc density.

Figure 30 shows that the relationships between thickening rates and floc-volume concentrations were similar for three of the ferric sludges. The exception was the sludge formed during the coagulation of high turbidity water at pH 7.8. It's thickening rate increased, probably because the characteristic sludge aggregate size increased. That conclusion is based on the observed significant increase in aggregate size of ferric hydroxide sludges formed at higher pH (reported previously in this chapter). The high AVI value associated with this sludge is indicative of a low aggregate density, thus eliminating density as a reason for a more rapid thickening rate.

Finally, it should be noted that the slopes of the lines on semilogarithmic plots of settling velocity versus aggregate volume fraction (I_a) were similar for all the hydroxide sludges tested. Though some variation was evident, the thickening rates of these sludges could be described by the following equation:

$$V = V_o 10^{(-kI_a)} \qquad (4\text{-}1)$$

where V_o is believed to represent the average Stokes' law settling velocity for the sludge aggregates, I_a is the aggregate volume fraction, and k is an empirical constant. The average k value for both ferric and aluminum hydroxide sludges was 2.85. Also, the range of k was rather small (2.68-3.15), which suggests that this value may be applicable to a variety of similar chemical sludges.

The importance of sludge density differences extends to specific resistance values as well. Gale (41) described the specific resistance (r) using the following equation:

$$r = \frac{36K\,(1-E)}{d_e^2\,E^3\,\rho_p} \qquad (4\text{-}2)$$

here K is a parameter that varies with shape and other factors, E is the porosity of the sludge cake, ρ_p is the bulk density of the sludge, and d_e is the equivalent diameter of the mixture of sludge particles. Shape factors were not investigated in the course of the present study and were assumed to have negligible effect. However, the remaining variables in the equation were investigated.

As suggested in the previous equation, sludges composed of smaller particles have higher specific resistance values (all other factors being equal). This effect of particle size on specific resistance values has been demonstrated by Knocke *et al.*, (50) with heavy metal sludges and by Knocke and Wakeland (32) with water treatment sludges. However, a review of the data presented by Knocke and Wakeland (32) revealed a consistent correlation between increased sludge bulk densities and decreased specific resistance values for the sludges tested.

The expected effect of particle size variations on specific resistance values was not found during this study. In fact, the sludges with the highest percentage of small particles and smaller average particle size were those with the lower specific resistance values. This eliminated the possibility of the presence of fines or average particle size from being the parameter of primary importance. Thus, it was hypothesized that floc density was a controlling factor in defining the dewatering rates of the coagulant sludges examined during this study.

The specific resistance equation proposed by Gale (41) can be used to show that density can affect specific resistance in two ways. First, specific resistance is proportional to the inverse of the bulk density of the sludge. Evidence showing the dependence of settled solids concentrations (bulk densities expressed on a percent weight basis) on coagulation pH, influent turbidity, and the coagulant dose/influent turbidity ratio has been presented previously in this chapter.

Second, the porosity (E) term in the equation is also effected by differences in primary sludge particle density. As the sludge used during specific resistance testing was previously gravity thickened, the particles of primary importance during mechanical dewatering most probably were sludge floc. Therefore, the sludge bulk density (ρ_p) can be described by the following equation:

$$\rho_p = (1-I_f)\rho_w + (I_f)\rho_f \qquad (4-3)$$

where ρ_w is the density of water, ρ_f is the average sludge floc density, and I_f is the floc volume fraction. Substituting E for $(1-I_f)$ into the above equation and rearranging, the following equation can be obtained:

$$E = (\rho_p-\rho_f)/(\rho_w-\rho_f) \qquad (4-4)$$

This equation shows that E increases as ρ_f increases (assuming ρ_w and ρ_p remain constant and ρ_p is greater than ρ_w). Therefore, by Gale's equation, specific resistance is also inversely related to ρ_f.

Although ρ_f was not measured directly, it may be hypothesized that ρ_f can be approximated by the final dewatered cake solids concentration. Figure 16 displays data which show that the final dewatered cake solids concentration (in effect ρ_f) increased as pH decreased from 8.0 to 6.0. Also, ρ_p is directly related to the settled solids concentration, as is shown in Equation 3-2. Figure 13 shows the increase in settled solids concentration that occurred as pH decreased from 8.0 to 6.0. These results, correlated with those in Figure 14, show that ρ_f and ρ_p, and specific resistance are inversely related.

Effluent Turbidity Considerations

As was true of all the sludge characteristics tested, effluent turbidity levels were influenced by the coagulation pH and influent turbidity levels. Marked deterioration of effluent quality occurred below pH 6.8 in the continuous-flow unit when alum was the coagulant (Figure 31). This was in contrast to jar-test results obtained using a treatment scheme similar to that in the continuous-flow unit. Turbidities were reduced in jar-tests from 50 NTU to 4.1, 1.8, and 5.6 NTU at pH 8.1, 7.0 and 6.2, respectively, after 30 minutes settling. This difference between jar-test and continuous-flow results suggests that the application of jar-test results to continuous-flow systems may be questionable.

Neither densities or particle size distributions given previously suggest effluent quality degradation occurred at coagulation pH below 6.8. Therefore, it may be hypothesized that particle stability is the cause of effluent degradation. This view is supported by data in Table 4 that show a significant decrease in the percentage of particles between 2 and 10 microns in diameter removed during clarification as pH decreased from 8.2 to 6.0. This particle size range was

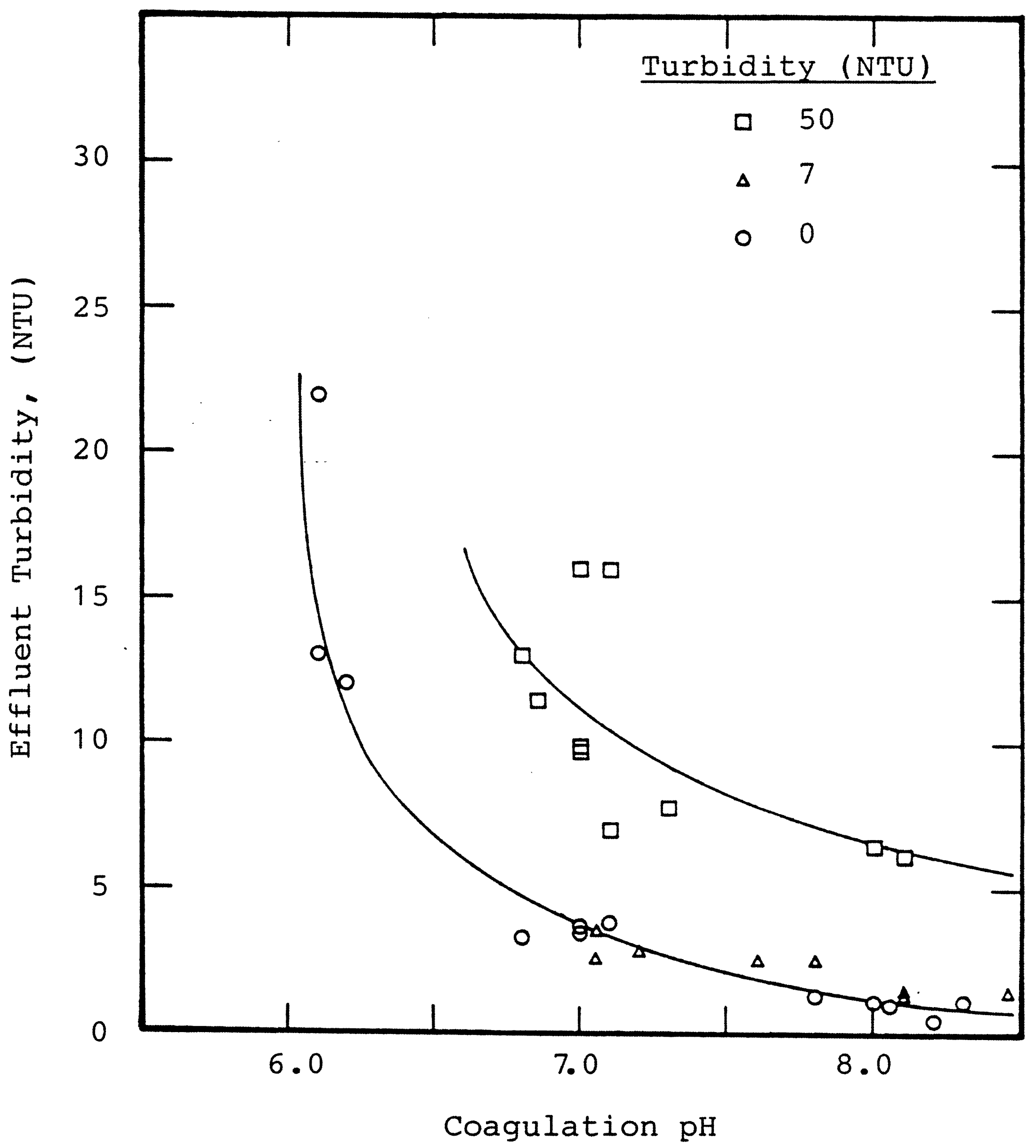

Figure 31: Variations in effluent turbidity as a function of coagulation pH and influent turbidity. (Alum dose was 80 mg/L).

Table 4. The effect of influent turbidity and coagulation pH on aluminum hydroxide floc between 2 and 10 microns in diameter.

Turbidity (NTU)	pH	Concentration Prior to Clarification (No./mL)	Concentration in Effluent (No./mL)	Percent Removed During Clarification
	8.1	6,330	392	93.8
0	6.8	8,810	1,520	82.8
	6.1	20,300	10,600	47.8
	8.1	32,100	4,850	84.9
50	6.8	121,000	35,700	70.5
	6.1	126,000	116,000	7.9

thought to be indicative of effluent turbidity as it represented greater than 99.5 percent of the particles present in the pilot-plant effluent at pH 6.0-6.2. Repulsion of like-charged particles may be responsible for particle stability below pH 6.8, as aluminum hydroxy species become more positively charged as pH decreases from 7.0. However, it is important to note that the theoretical detention time in the clarifier used in this study was only one hour; longer detention times may have significantly improved effluent quality.

The effluent turbidity decreased slightly as the pH increased in the range of 6.8 and 8.0. This suggests a slight increase in the capture efficiency of the floc produced at higher pH. Particle size analyses showed a reduction in very fine particles present in the flocculator in this pH range (Table 4).

Similar relationships between turbidity and pH are apparent in the ferric system data shown in Figure 32. However, the effluent quality of this system deteriorated below pH 6.3. Because of the limited data presented, no conclusions can be drawn concerning the effects of influent turbidity on the effluent quality of the water treated with ferric chloride.

Applications

In the course of this study, it has clearly been shown

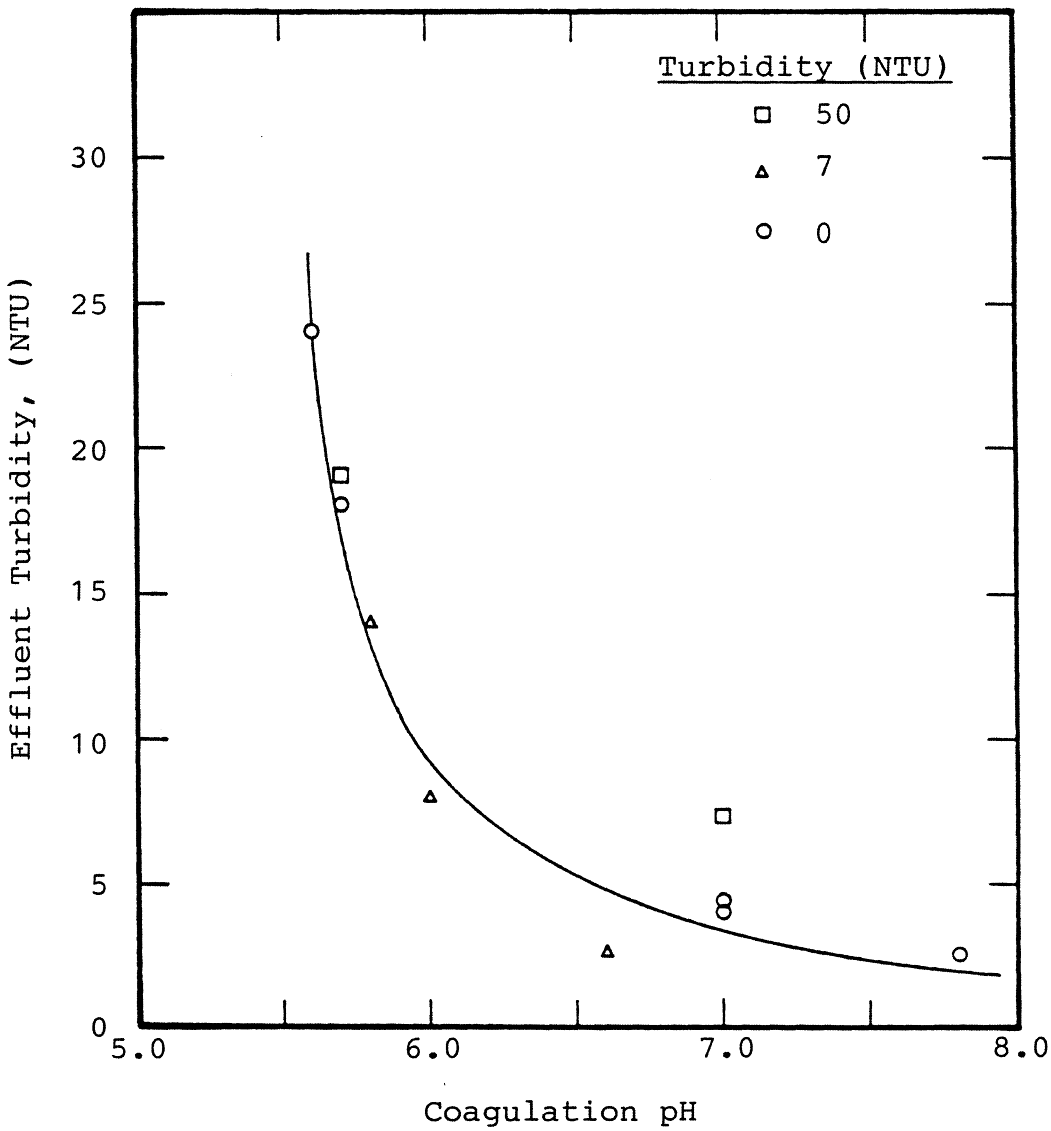

Figure 32: Variations in effluent turbidity as a function of coagulation pH and influent turbidity. ($FeCl_3$ dose was 39 mg/L).

that sludge thickening and dewatering characteristics can be modified through changes in influent turbidity levels, coagulation pH and coagulant dose/influent turbidity ratios. However, a trade-off appears to exist between improving sludge characteristics and pre-filter water quality, and therefore, filter-run length. Due to the short, one-hour detention time of the clarifier used in this study (Virginia design standards require a minimum detention time of 4 hours), further testing of the post-clarifier water quality under low pH conditions will be required to determine the feasibility of operating under such conditions. Testing to determine the characteristics of coagulant sludges produced during charge-neutralization coagulation would also be worthwhile.

SUMMARY AND CONCLUSIONS

The purpose of this study was to determine the effects of coagulation pH and influent turbidity on the thickening and dewatering characteristics of aluminum and ferric hydroxide sludges. The role of sludge particle size and water content in determining sludge thickening and dewatering characteristics was also investigated. Quantities of sludge were produced under specific conditions in a 400 L/day, continuous-flow pilot-plant. Effluent turbidity levels were monitored during sludge production to correlate treatment efficiency and sludge characteristics.

Based on the results of this study, the following conclusions were made:

1. Aluminum and ferric hydroxide sludges that are produced under conditions of high influent turbidity or low pH thicken and dewater more rapidly and to a greater extent than sludges produced under conditions of low influent turbidity or high pH. Also, sludges formed under low alum dose/influent turbidity ratio conditions thicken and dewater more rapidly and to a greater extent than those produced under high alum dose/influent turbidity ratio conditions.
2. The density of sludge floc is the dominant factor in determining sludge thickening and dewatering characteristics. Increases in sludge-floc density

correlated well with increases in the rate and extent of thickening and dewatering. The predicted effect of particle-size variation on sludge-dewatering rates was not found during this study and was assumed to be secondary to the effects of density.

3. Operating conditions that produced sludges with superior thickening and dewatering characteristics consistently produced high turbidity effluent. Because neither particle-size or density data could explain these occurrences, increased particle stability was thought to be responsible. Further research will be required to isolate the cause of the effluent degradation and to determine if increases in sludge floc density due to pH reduction are directly linked to this mechanism.

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