EFFECT OF VARYING OPERATIONAL PARAMETERS ON THE DRAINABILITY OF FREEZE CONDITIONED CHEMICAL SLUDGES

by

Larry Michael Simmons

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APPROVED:

Paul H. King, Chairman

Clifford W. Randall

N. T. Stephens

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I. INTRODUCTION

The two principal products of water and wastewater treatment are product water or treatment-plant effluent and byproduct slurries or sludges. Byproduct sludges are not finished products of the water and wastewater treatment processes. Since the objective of such treatment is to concentrate impurities from respective flow streams, proper sludge processing is necessary to insure hygienic safety and ease of ultimate sludge disposal. It is also desirable that sludge treatment processes reduce the volume and weight of the material to facilitate handling and produce an acceptable end-product.

In wastewater treatment, sludge handling and disposal is often the most complex problem an engineer faces. In dealing with wastewater sludge, an engineer must remember that it is composed largely of the offensive substances in untreated sewage; that, when the sludge is a product of biologic activity, the offensive substances have changed form but are still subject to degradation; and that by far the largest fraction of the composition of sludge is water.

Certain substances are unaffected by the primary and secondary processes used in normal wastewater treatment. These substances include simple inorganic ions, such as calcium, potassium, sulfate, nitrate, and phosphate, and ever-increasing concentrations of complex synthetic organic compounds. As the effects of these substances are better understood, Federal and State authorities have required removal in certain locations. Removal techniques may be physical, chemical, or biological in nature. Application of these processes may frequently accentuate the problems associated with sludge disposal.

Water treatment plant sludges have not historically received the attention directed to wastewater sludges. Untreated discharge to receiving streams has been widely practiced because engineers and operators, until recently, felt that this practice only returned to the stream those substances which had been removed during treatment. The dynamic biological, esthetic, and economic effects of untreated sludge discharge to a stream are now realized. An untreated discharge may upset chemical equilibrium, decrease fish spawning areas, and smother the purifying organisms on the stream bottom. Sludge deposits are easily stirred by current action, marring the esthetics of a natural watercourse. Direct disposal of sludge to a stream also inflicts the economic burden of removal on the next water user.

Water treatment plant sludges are derived from two sources, (1) the sediments from the bottom of coagulation and sedimentation basins, and (2) the substances dislodged in the filter backwashing operation. Basin sediments include organic and inorganic materials such as plankton, clay particles, microorganisms, and precipitates in varying amounts, depending upon the raw water source and the time of year. Filter backwash is composed of low solids content sludge consisting of plankton, algae, very fine clay particles, and some hydroxides of the coagulants being used in treatment. Of the two sources, the sedimentation basin sludge constitutes the greatest solids disposal problem.

Coagulation is practiced in water treatment to enmesh and combine settleable solids with suspended and colloidal solids, resulting in rapidly settling aggregates or flocs. Chemical coagulation can also produce the same result in wastewater treatment. More recently though, attention has been focused on the ability of chemical addition to remove phosphorus. Additionally, chemical precipitation, when coupled with activated carbon adsorption, may eliminate the need for a biological treatment process, while improving the normal organic removal efficiency attainable with a biological process.

Various methods have been suggested, tested, and used for treatment of water and wastewater sludges. Metcalf and Eddy, Inc. (1) report chemical addition and heat treatment as the most common wastewater sludge conditioning techniques. Other conditioning processes include freezing and irradiation. Conditioning is performed for the express purpose of improving dewatering characteristics. A partial list of ultimate dewatering and disposal techniques includes:

(1). drying beds
(2). vacuum filtration
(3). centrifugation
(4). filter pressing
(5). vibration
(6). incineration and wet oxidation
(7). land disposal
(8). ocean disposal.

Albrecht (2) lists the following methods as applicable for handling water treatment plant sludges:

(1). direct discharge to surface waters
(2). sand-bed drying
(3). lagooning
(4). filter pressing
(5). vacuum filtration

(6). centrifugation
(7). freeze-thawing
(8). disposal to sanitary sewers.

Of particular interest in this report is the fact that freeze-thawing as a conditioning technique has been found to be applicable to both water and wastewater sludges. This process has proved to be a very successful method to enable dewatering of all types of sludge. Laboratory investigations indicate that freezing of sludge is frequently more effective than chemical conditioning in improving sludge filterability (1). Freezing dehydrates sludge particles and destroys colloidal structure. The freeze-thawing process can consistently yield in excess of twenty percent solids concentrations which can be conveniently handled.

Much work remains to be done before the freeze-thawing method of sludge conditioning can be applied effectively. The purpose of this research was to investigate the effect of solids content and time in the frozen state on the freeze-thawing method when applied to a variety of chemical sludges.

II. LITERATURE REVIEW

In order to investigate the effects which solids content and time in the frozen state have on the freeze-thawing process as a conditioning technique for chemical sludges, several diverse topics must be reviewed from the recent literature. The following sections summarize important aspects of coagulation theory, sludge characterization, developments in the use of freeze-thawing for sludge conditioning, and filterability theory and testing.

Coagulation Theory

Coagulation of colloidal particles, usually negatively charged, involves two basic steps: (1) transport of the particle so that contact with other particles is enhanced and (2) particle charge destabilization to promote particle attachment. Transport is a physical phenomenon caused by fluid movement or Brownian motion. Destabilization is a colloid-chemical reaction affected by physical and chemical properties of the liquid, colloid, or coagulant.

Although researchers generally agree on the transport mechanism, theories on the mechanism of destabilization can vary widely. Generally, destabilization is thought to occur by a combination of four methods: (1) double layer compression, (2) adsorption and charge neutralization, (3) enmeshment in a precipitate, and (4) adsorption and interparticle bridging. Double layer compression is the result of the addition of an indifferent electrolyte to increase the ionic strength of a solution and lower the energy barrier which must be overcome for aggregation. Adsorption and neutralization is the adsorption of a cation to the colloid surface, reducing its negative charge. Enmeshment in a precipitate is the result of the formation of hydroxide and phosphate precipitates with metal cations and the subsequent sweeping action of colloids with settling. Bridging is the result of polymers attracting colloids to unsatisfied charge sites on their long chained structures. The possibility exists for bridging between chains to enable sweeping of colloids out of suspension.

The sequence of events occurring when trivalent metal cations are used as coagulants probably begins with the precipitation of hydroxide and phosphate ions which share an affinity, similar in strength, for the cations (3). It is postulated that an amorphous combination of the two ions precipitates. However, phosphorus is frequently removed in excess of stoichiometric predictions. This effect can be explained by the fact that organic phosphorus compounds are surface active and may become adsorbed in precipitates. Also a substantial amount of phosphorus exists in suspended form and is removed by coagulation (4). After precipitation, the trivalent ions proceed to coagulate by methods described in a preceding paragraph.

Precipitation of lime requires dosing the solution until free carbonic acid of the bicarbonates is converted to calcium carbonate which acts as a coagulant. Calcium, hydroxide, and phosphate ions react to form hydroxyapatite. Coagulation then proceeds through the other destabilization steps.

Sludge Characterization

The intent of this section is to summarize current knowledge concerning the nature of the sludges utilized in this investigation, including: (1) a water treatment sludge derived from coagulation with aluminum sulfate (alum); (2) a water treatment sludge derived from coagulation with ferric sulfate; (3) an advanced wastewater treatment sludge derived from coagulation with ferric sulfate; and (4) an advanced wastewater treatment sludge derived from coagulation with lime.

Alum Sludge from Water Treatment Plants

Commercial aluminum sulfate reacts with natural alkalinity in water according to the following expression:

$$Al_2(SO_4)_3 \cdot 18H_2O + 3Ca(HCO_3)_2 \rightleftarrows 3CaSO_4 + 2Al(OH)_3\uparrow + 6CO_2 + 18H_2O.$$

Aluminum hydroxide is insoluble and aids in sweeping suspended matter from water and wastewater. A competing reaction is the precipitation of phosphorus.

Various sources have attempted to classify the characteristics of alum sludges (5,6,7,8). A consensus description would be that alum sludge is a non-Newtonian, bulky, gelatinous substance composed of aluminum hydroxide, inorganic particles such as clay or sand, color colloids, microorganisms including plankton, and other organic and inorganic matter removed from the water being treated (2). This gelatinous consistency makes the sludge relatively difficult to dewater.

Coagulation and sedimentation basin sludge is a greater problem than filter backwash sludge. Sedimentation sludge is generally low in total solids content, normally ranging from 3,000 to 15,000 mg/l. Suspended solids can amount to 75 to 90 percent of the total solids. Approximately 20 to 35 percent of the total solids are volatile. These solids are readily oxidizable but are not easily biodegradable as can be seen from comparison of reported BOD_5 and COD levels. Albrecht (2) noted a BOD_5 level of 30 to 100 mg/l and COD values 500 to 10,000 mg/l. These values are in agreement with those reported in the American Water Works Association Research Foundation Report (5). Bugg, et al., (9) report minimum BOD_5 values of a typical alum sludge to be 380 mg/l. Samples were acidified to remove aluminum. This procedure eliminates a majority of aluminum toxicity, but some toxicity was still evident. Alum sludge has a normal pH range of 5 to 7. Settling tests indicate that sedimentation basin sludge exhibits the characteristics of zone settling (7).

Filter backwash water is largely a hydraulic problem. From the standpoint of chemical characteristics, backwash sludges usually have total solids concentrations of around 400 mg/l with 40 to 100 mg/l of suspended solids (5). Turbidity is generally less than 2000 mg/l and BOD_5 and COD values are reported to be less than 5 mg/l and 160 mg/l, respectively.

A summation of these characteristics indicates that alum sludge: (1) is insoluble in the natural pH range of water; (2) is readily settleable, but to a concentration that is inadequate for convenient handling and subsequent landfill disposal; (3) is compressible and resists the passage of water from itself; and (4) has a composition that when disposed of on land will clog the soil (2).

Ferric Sulfate Sludge

Stumm and O'Melia (10) have suggested that the effects of iron salts as well as aluminum salts on coagulation are brought about by the hydrolysis products of the salts and not by simple aquo-metal ions. This hyrolysis can be represented as:

$$Fe(H_2O)_6^{+++} \rightarrow Fe(H_2O)_5OH^{++} \rightarrow Fe(H_2O)_4(OH)_2^{+} \rightarrow Fe(H_2O)_3(OH)_3 \rightarrow$$

$$Fe(H_2O)_3(OH)_4^{-}. \quad (10)$$

As can be seen, the hydrolysis is accomplished by stepwise consecutive replacement of water molecules by hydroxide ions. After hydrolysis, destabilization and precipitation occur as outlined previously.

The characteristics of sludges produced as a result of water and wastewater coagulation with iron salts are not as widely known as alum sludges. Ferric sulfate is used in water treatment for three basic reasons: (1) color can be removed economically and efficiently with proper coagulation; (2) colloidal dispersions containing iron are more effectively destabilized with the iron salt than with lime or alum; and (3) manganese can be effectively removed by the salt in the pH range 9 to 10 (11). Additionally, ferric sulfate can be used to effectively precipitate phosphorus in wastewater treatment.

Water and wastewater sludges produced by ferric sulfate coagulation are similar in characteristics. The sludge possesses the reddish-brown color characteristic of oxidized iron compounds. The pH range can vary from 3 to 10, but optimum phosphorus precipitation occurs between 4.5 and 5.0. The total solids content of sedimentation basin sludge is frequently higher than that of alum systems, ranging from 0.2 percent to 5 percent. The sludge is feathery and bulky at a dilute concentration, but tends to be heavy and resistant to shear at higher concentrations (11). Most of the total solids are in the suspended form. COD values are comparable to those of alum sludge, 500 mg/l to 15,000 mg/l. Although ferric sulfate sludge is considered to settle and filter better than alum sludges, its somewhat gelatinous consistency does not always allow for ready dewatering.

Lime Sludge

The chemistry of lime as a coagulant is entirely different from that of aluminum or iron salts. Lime addition to water or wastewater results in the following reactions:

$$Ca(OH)_2 + Ca(HCO_3)_2 \rightarrow 2CaCO_3\downarrow + 2H_2O$$

$$Ca(OH)_2 + Mg(HCO_3)_2 \rightarrow CaCO_3\downarrow + MgCO_3 + 2H_2O$$

$$MgCO_3 + Ca(OH)_2 \xrightarrow[10]{pH} Mg(OH)_2\downarrow + CaCO_3\downarrow$$

$$10Ca(OH)_2 + 6H_3PO_4 \rightarrow Ca_{10}(PO_4)_6(OH)_2\downarrow + 20\ H_2O. \quad (12)$$

These reactions indicate that, depending on initial alkalinity, large dosages of lime may be required to satisfy competing reactions before phosphorus precipitation.

There are three basic characteristics which make lime a good coagulant: (1) effective and economic color removal; (2) effective removal of phosphates from secondary effluents; and (3) dewaterability exceeding that of alum or iron sludges (13). Lime sludges usually range in pH from 9.5 to 11.5. Optimum phosphorus removal occurs between pH 11.0 and 11.5. Good dewatering properties can be attributed to the dense granular nature of the calcium carbonate floc and the resulting higher specific gravity of the lime sludge. These characteristics have aided in attaining solids contents of up to 50 percent for water softening sludges (14). COD levels, suspended solids levels, and volatile solids levels are comparable to those noted for aluminum and iron salts.

The Freeze-Thawing Process as a Conditioning Technique

Following the publication of a letter in Nature in 1947, dealing with freezing as an aid in drying of agricultural humus, Clements, Stephenson, and Regan (15) conducted experiments to determine the applicability of freezing as a means to accelerate dewatering of wastewater sludge. When "test-tube" scale experiments demonstrated great improvement in filterability of digested sewage sludge, experimental work was expanded to cover a wide range of parameters. From these early experiments, a specially designed freezing machine was created as part of the experimental apparatus. The machine was equipped with coils above which freezing pans were situated. The refrigerant in the coils was methyl chloride which was recycled to act as a condenser and evaporator. This system utilized the latent heat of fusion of one batch of previously frozen sludge to cool the hot refrigerant being circulated to freeze the next. The cooling of the refrigerant was effected at a low temperature by the continuously melting sludge-ice, and at the same time the thawing was accomplished without the necessity of supplying external heat for the purpose.

A summary of the results obtained by Clements, *et al.*, follows:

1. The settling of all sewage sludge, primary, activated, and digested, was promoted by freezing.

2. Settling was accelerated by freezing with chemicals, but the percentage settlement at the end of an hour was approximately the same whether chemicals were used or not.

3. Filtration, after freezing with chemicals, was remarkably accelerated. Filtration times in the best cases were reduced to a few seconds and produced 3/8-inch cakes. The filter cakes were friable and of high solids content, being over 30 percent in some instances.

4. The chemicals used were chlorinated ferrous sulfate, chlorine gas, and aluminum sulfate, and doses were up to 1000 parts per million of the active ion.

5. The best results were obtained by use of aluminum sulfate, dry solids production reaching 350 lbs/sq ft/hr. In the case of chlorine, the maximum dry solids production appeared to be about 40 lbs/sq ft/hr.

6. Complete freezing was essential. Freezing had to be fairly slow. "Flash" freezing was ineffective.

7. Some saving of the latent heat of fusion was practicable in a suitable installation.

8. The method of thawing was immaterial as long as it was not associated with vigorous agitation.
9. The supernatant liquids on settlement were, on an oxygen absorption basis, not much worse than ordinary sewage (15).

Clements, Stephenson, and Bruce began full scale operation of sludge freezing at Northern Outfall Works, London, England in 1950 (16). The objective was to produce one ton of ice per day and develop filtration techniques after thawing. The freezing machine was modified to eliminate the use of latent heat of fusion and thawing was accomplished with steam and hot water. Methyl chloride was conducted through coils in a brine solution into which sludge containers were lowered for freezing. This operation did not produce the desired result since the brine solution temperature had to be raised between freezing batches to eliminate quick-freezing. The researchers also experimented extensively with a large number of filter cloths on a large Buchner funnel apparatus. Previous experimentation with rotary vacuum filtration and centrifugation proved these methods inadequate. Synthetic filters produced promising results with filtration times from 15 to 75 seconds and dry cake solids levels ranging from 26.6 to 29.0 percent. However, the problems which remained were threefold: (1) high cost and consumption of power; (2) high capital and operating cost when using both refrigeration and vacuum filter equipment; and (3) frequent washing of filter media.

Application of the freeze-thaw technique to water treatment sludge was first investigated by Peter Doe of the Fylde Water Board, Blackpool, England (17). With the apparent growing inadequacy of lagooning as a disposal method at the Stocks Filtration Plant, Doe began a series of tests similar to those performed by Clements and colleagues. In total agreement with the results of previous research, it was determined that: (1) time to freeze was critical, i.e. quick freezing was inadequate; (2) freezing temperature was unimportant; (3) remaining in the frozen state, even a brief period of time, improved filterability over a sample thawed the instant it had frozen solid; (4) freezing a sample completely was mandatory; (5) temperature at which frozen sludge was stored and thawing time were unimportant; (6) initial sludge thickness had no noticeable relationship to filtering time; and (7) the physical change which transpired during freezing was irreversible. When compared to filter pressing and heat treatment methods, Doe concluded that freezing was an attractive process, even on an economic basis, for conditioning and disposal of alum sludges.

Doe, Benn, and Bays (18) theorized that the dramatic effect of freezing on solids dewatering was due to ice crystals formed when freezing commenced. As temperature fell, the particles of sludge were dehydrated and enmeshed in ice. The resulting ice pressure caused coalescence of sludge particles into fine hard grains. The pressure was released upon thawing allowing the grains to settle quickly. Evidence for this theory was found by experiments on two important aspects: (1) visual inspection of slowly frozen sludge showed the fine grains embedded in clear ice and (2) "flash" freezing, where the sludge was frozen instantaneously, resulted in a dark brown opaque mass which, after thawing, reverted to the original gelatinous state.

The Fylde Water Board was the first to employ freezing for full-scale sludge disposal. By the time construction began, the competitive cost estimate Doe had reported was no longer applicable. It was necessary to construct facilities to concentrate 33,000 gpd of 0.5 percent solids sludge to approximately 2.4 percent solids by slow stirring (19). The freezing process consisted of passing ammonia refrigerant through coils in a batch tank containing the sludge, while thawing was accomplished by using the same coils as a condenser. Sludge cycle times varied between 50 and 120 minutes. Initial capital costs were $17,000 per 1000 gallons of sludge while power consumption ranged between 180 and 230 kilowatt-hours per 1000 gallons of sludge frozen (20). In 1969, polyelectrolyte addition improved sludge thickening to six percent solids entering the freezing plant. Lagooning for final clarification resulted in a solids content of between 40 and 70 percent (21). Supernatant water was discharged to a receiving stream and solids were used for agricultural humus or in a landfill.

Katz and Mason (22) experimented with freezing activated sludge in an attempt to solve problems experienced by Clements, et al. Activated sludge from the Milwaukee Water Pollution Control Plant was frozen in a commercial freezer and thawed in a hot water bath. Thawed samples were gravity drained through various size wire screens (140 to 24 mesh) placed in 9 cm Buchner funnels and supported by an 18 mesh wire pad. A three inch mercury vacuum was applied after gravity drainage ceased.

The same dramatic dewatering results were obtained as had been noted by previous investigators. For a one percent raw solids sample, gravity and pressure drainage was essentially complete from a one liter sample in 50 seconds. Variation in feed solids concentration indicated that dewatering time decreased as solids increased for the same solids loading to the filter. Cake solids for the freezing process were determined to be comparable to those of conventional vacuum filters, ranging from 13 to 25 percent. Filtrate suspended solids were less than 250 mg/l for screen mesh sizes 40 to 140. At 24 mesh, suspended solids rapidly ran over 400 mg/l but this level remained well below vacuum filtration operations which usually yield filtrate solids ranging from 500 to 10,000 mg/l (22).

Katz and Mason, as Doe and colleagues, theorized that dehydration and flocculation due to pressure were the mechanisms responsible for the success of freezing (22). It was determined that dehydration did not occur in "flash" freezing and that flocculating pressures were never obtained. The final conclusion was that freezing rate must be regulated so that dehydration will occur.

Cheng, Updegraff, and Ross (23) attempted to solve the problem of long freezing times and high temperature differences previous researchers had determined necessary for optimum dewatering by mechanical means. Samples of primary, activated, return activated, and digested sludge were frozen in brass cannisters with 290 sq cm of surface area for heat transfer. Samples were frozen in a stirred, controlled-temperature bath of ethylene glycol. Alum was the only conditioning chemical added to the sludge. Cheng observed that an ice film of small thickness possessed a thermal admittance of about 200 BTU/sq ft-°F-hr, high enough to permit rapid removal of heat even at small temperature differences. With an average heat transfer coefficient, U, of 12 BTU/sq ft-°F-hr and a temperature difference from the bath to the sludge of -3°C to -5°C, dry cake solids after filtration indicated results comparable to those of Clements, Stephenson, and Regan, while freezing time was reduced to ten minutes. Increased cooling bath agitation resulted in a transfer coefficent of 29 BTU/sq ft-°F-hr and dry cake solids similar to the previous case, but at a freezing time of five minutes (23).

The conclusions drawn from these experiments was that the success of thin film, high-rate freezing at small temperature differences could be utilized to reduce the high costs and power consumption of the freezing process. Additionally, it was apparent that a continuous process was available where batch processes had been used previously (23).

The most extensive research on the freezing process as a conditioner for sewage sludges was funded by the Environmental Protection Agency and conducted by Rex-Chainbelt, Inc., on behalf of the Milwaukee Sewerage Commission. The investigation included: (1) evaluation of physical and chemical changes that occur as a result of freeze conditioning and dewatering and the relation of these changes to the fertilizer properties and characteristics of the dried sludge; (2) evaluation of the effect of freeze conditioning of waste activated sludge at the

Milwaukee Sewerage Commission Water Pollution Control Plant on solids dewatering characteristics; (3) reduction or elimination of the need for chemical sludge conditioning in the vacuum filtration dewatering process in use at the Milwaukee plant, and (4) investigation and evaluation of new techniques for sludge dewatering through the design and demonstration of a continuous gravity screen filter (24). Bench scale and field tests were performed on various parameters, including:

(1). freezing method
(2). storage time before freezing
(3). thawed storage time
(4). storage time in the frozen state
(5). freezing time
(6). partial freezing
(7). mobility of sludge during freezing
(8). chemical additives
(9). shape or configuration in which sludge is frozen.

As with previous researchers, it was determined that complete freezing was necessary and dewatering was greatly improved with a slow freezing rate. Added chemicals, such as ferric chloride, greatly improved dry cake solids. Increased storage time before freezing and after thawing resulted in decreased dewaterability of sludge cakes. Storage in the frozen state to 16 hours significantly benefited cake solids content and drainage rate. Shape and configuration studies revealed that a sludge layer approximately one-half inch thick produced optimum cake solids content. This result verified the research of Cheng and colleagues, but freezing at small temperature differences was not attempted (24).

New parameters studied by Rex-Chainbelt, Inc. included the effect of relative motion between sludge and freezing medium during freezing and the effect of the method of freezing. It was easily determined that relative motion between sludge and freezing medium produced effects similar to partial freezing, i.e., very poor dewaterability. It was determined that direct refrigeration, in which the refrigerant was in direct contact with the sludge, was not successful in that difficulties were encountered in freezing the sludge completely or dewatering properties of the thawed sludge were unsatisfactory. Indirect refrigeration, in which the refrigerant is contained in a vapor compression refrigeration cycle, produced results similar to those of previous researchers (24).

The overall conclusions drawn from the research by Rex-Chainbelt, Inc. were threefold:

1. The freeze-conditioning concept, from the standpoint of technical process efficiency, has definite merit as a means of conditioning waste activated sludge for subsequent dewatering.
2. Engineering evaluation of the freeze-conditioning process and comparison with the conventional chemical conditioning method showed capital outlays, operating costs, and space requirements were excessive for the freezing method.
3. Reduction of freeze-conditioning operating costs would be realized only at the expense of increasing capital outlay and, therefore, afforded no real reduction (24).

The project was discontinued after engineering estimates showed that research efforts should be directed toward other dewatering techniques.

While attempts were being made to solve the problems involved with mechanical freezing of sludges, several researchers were investigating the effect of northern latitudes on lagoon systems. The SΦndersΦn

Filtration Plant in Copenhagen, Denmark, has been practicing natural freeze conditioning for some time (5). After two years operation of gravel-bottomed lagoons, alum sludge dewatered to a four cm layer of solids which were easily disposable.

Fulton and Bishop (25) have studied the effect of natural freezing on alum sludge at Monroe County Water Authority Plant near Rochester, New York. Initial laboratory freezing of sludge samples indicated that total solids concentration could be increased from 3.5 to 17.5 percent and a significant volume reduction occurred. A lagoon, which had been filled during a cold period in January, 1968, was tested to determine if natural freezing had affected the surface solids content. Since the lagoon had been filled according to normal operating procedures and not controlled for optimum use of natural freezing, it was expected that the results of solids testing would be considerably less than laboratory results. The 8.1 percent solids concentrations obtained determined that a test lagoon should be utilized for specifying design parameters for future lagoon construction to take advantage of natural freezing. In 1968, the lagoon was filled with 0.3 percent solids clarifier sludge to a depth of 30 inches. After thawing and standing through August, 1968, the supernatant was decanted, leaving a solids depth of about five inches and a 35 percent solids level. The supernatant was clear and contained only five mg/l suspended solids. After one week of dry weather with air temperatures in the 80°F range, the sludge dried to a consistency suitable for handling and disposal as landfill, and containing less than 50 percent moisture (26). The authors stated that generally two lagoons would be necessary for full-scale operation, one to settle and store while the other was in a freezing cycle during winter months (25). Both lagoons should be sized to hold one year's sludge flow and follow sound construction practices for lagoons.

Farrell, et at., (27) have attempted to provide basic information essential to adequate design of facilities for dewatering aluminum hydroxide sludges by natural freezing. Both water and wastewater sludges were subjected to the climates of Ely, Minnesota and Cincinnati, Ohio, under controlled conditions. Conclusions drawn from the study were that: (1) aluminum hydroxide and water froze at similar rates; (2) snow cover was a serious obstacle to cold climate natural freezing facilities because of its insulating effect; (3) slow and complete freezing dramatically increased dewaterability and solids content; (4) repeated cycles of freeze-thaw increased dewaterability and solids content, but to a lesser degree than slow, complete freezing; (5) natural freezing in a mild climate, such as Cincinnati, required application of thin layers of sludge and could result in excessive management costs; and (6) phosphorus content of a sludge had only a slight effect on filterability and solids content (27). Two measures used by Farrell and colleagues to indicate the success of freezing on dewaterability were specific resistance and total organic carbon. Specific resistance, a measure of resistance to filtration, was approximately 10×10^8 sec^2/gm for unconditioned samples and 5×10^6 sec^2/gm for conditioned samples. Total organic carbon measurements on supernatant from freeze conditioned samples indicated that 99 percent of all carbon was in the solids (27).

Logsden and Edgerley (28) contradicted previous theories of freezing with results of experimentation on barium sulfate, iron and aluminum hydroxide, and water treatment alum sludges. It was determined that compressive pressure by ice was not necessary to dewater sludge. Samples were frozen from the bottom to the top at a fixed velocity. A gross migration of solids occurred to the top of the samples where gelatinous floc was consolidated due to increased moisture tension, a result of dehydration occurring as the particles migrated. Dewaterability of samples in which solids were captured by an advancing ice interface was not affected if a sample was allowed to completely freeze. The conclusions drawn from the Logsden and Edgerley research were that: (1) initial results approximated a freezing speed of 60 mm per hour as being the upper limit for effective sludge dewatering; (2) since compressive freezing was not needed for sludge dewatering, sludge could be frozen in thin layers on a flat surface, demonstrating the adaptability of the freezing process to mechanization; (3) polymer addition to freezing samples substantially lowered the specific resistance of particles to the flow of water, allowing for increased freezing speeds; and (4) natural freezing of lagoons might be aided if sludge were sprayed from nozzles over the lagoon surface (28). Again, the research of Logsden and Edgerley indicated the adaptability of freezing to mechanization resulting in an economic situation which would be competitive with other conditioning measures.

Sludge Filterability

Laboratory methods of measuring the extent to which a sludge dewaters include time required to collect a certain volume of filtrate passing through a filter media, occasionally under partial vacuum refiltration methods, and the Buchner funnel method of measuring specific resistance.

Specific Resistance

Perhaps the most widely used test to determine the filterability or drainability of a sludge is the Buchner funnel specific resistance test. It has been commonly employed as a control parameter for vacuum filtration processes.

The theory of average specific resistance had its origin in the work of Ruth, *et al.*, (29) and Carman (30). Ruth attempted to solve a problem of correlating actual experimentation with early theoretical derivations in filterability. Carman expanded the work of Ruth to the point that early formulations, generally used for ideal, non-compressible sludges, could be applied to any given sludge under constant pressure conditions.

Coackley (31) and Coackley and Jones (32) proposed use of Carman's theory rather than previous workers because it accounted for major variables affecting filtration, i.e., applied pressure (P), filter' area (A), solids concentration (C), and viscosity of filtrate (μ) (31). The rate of filtration can be expressed as:

$$\frac{dV}{d\Theta} = \frac{PA^2}{\mu(rCV + R_m A)}$$

where V is the volume of filtrate obtained at time Θ
r is the specific resistance of the sludge
R_m is the resistance of the filter medium.

By integration, for constant pressure,

$$\frac{\Theta}{V} = \frac{\mu rC}{2PA^2} V + \frac{\mu R_m}{PA} \qquad (31)$$

which may be written

$$\frac{\Theta}{V} = bV + a$$

where $b = \frac{\mu rC}{2PA^2}$ and $a = \frac{\mu R_m}{PA}$ (31).

Therefore, sludge resistance is determined by the expression:

$$r = \frac{2PA^2 b}{\mu C}$$

where r = specific filtration resistance, sec^2/gm
P = pressure of filtration, gm/sq cm
A = filter area, sq cm
b = slope of T/V versus V curve, sec/cm^6
where T = Θ = time, sec
V = volume of filtrate, ml, in time T
μ = filtrate viscosity, poise
C = ratio of grams of dry cake solids per gram of liquid before filtration, gm/cu cm (32).

Specific resistance measurements are a useful means of comparing the effectiveness of various methods of conditioning sludges. Coackley (31) found that ferric chloride addition to a 12 percent solids content digested wastewater sludge decreased specific resistance by a factor of 100, i.e., the rate of water removal increased 100 times. Experimentation with sludges coagulated with ferric chloride and conditioned by freeze-thawing reduced specific resistance by a factor of 1000. Bugg (33), Olver (34), and Argo (13) concluded that specific resistance is a qualitative measure of sludge dewaterability for polyelectrolyte-conditioned alum, ferric sulfate, and lime sludges, respecitvely. These results agreed with those of Gates and McDermott (35) who concluded that the dosage versus specific resistance relationship was a valid measure of the effect of polyelectrolyte conditioners on dewatering characteristics of alum sludges.

Refiltration

Various properties of dispersions have been used to follow the change from dispersed to flocculated systems, some of the more important parameters being turbidity of the supernatant, sediment volume, subsidence rate, and filtration rate (36). Filtration rate, or refiltration, involves the measurement of the time to refilter a given volume of supernatant solution through a deposited cake of flocculated particles.

Filtration rate, as specific resistance, is derived with respect to its theoretical foundation from the work of Carman. Carman, drawing on previous work of Kozeny, has shown that for a bed (filter cake) of constant and known thickness, the volume rate of flow of filtrate (Q) is related to other factors as follows:

$$Q = \frac{\Delta P g A \xi^3}{K \eta L S^2}$$

where Q = volume rate of flow of filtrate, cm^3/gm
ΔP = pressure drop across the bed, gm/cm^2
g = acceleration due to gravity, 980 cm/sec^2
A = cross-sectional area of the bed, cm^2
ξ = porosity of the bed [volume of the void divided by total of bed (AL)]
  where $\xi = 1 - W/AL\rho$
    W = weight of solid in the bed, gm
    L = depth or thickness of bed, cm
    ρ = bulk density of solid, gm/cm^6
η = viscosity of fluid passing through bed
K = constant $\simeq 5$
S = surface area of particles in unit volume of bed, cm^2/cm^3 (41).

In order to measure the filtration rate through a filter cake of constant and known thickness, the first filtrate is passed through the cake obtained from the initial filtration in which the solid is still settling during the process. This second, or refiltration rate, is used as the Q in the Carman-Kozeny equation. Refiltration eliminates any variations due to the build-up of the bed during filtration.

LaMer and colleagues (36, 37, 38, 39, 40, 41, 42, 43) have effectively used the refiltration parameter to determine the effect of polyelectrolyte conditioning on silica and clay dispersions and phosphate slimes. They concluded that optimum polyelectrolyte dosages can be determined by measuring refiltration rates. For example, tests with silica and non-silica dispersions indicated that non-silica suspensions required an optimum dose from 300 to 1500 mg/l while silica dispersions required only 0.3 to 10 mg/l. At the same time, refiltration improvements ranged from 800 to 7000 percent for non-silica dispersions, compared to a maximum of 330 percent for silica dispersions.

LaMer (38) used two methods of measuring refiltration rates: (1) gravity and (2) pressure. The vacuum filtrations were performed using a seven centimeter Buchner funnel and number 2 Whatman filter paper at a pressure of 74 centimeters mercury. The gravity refiltration method utilized number 2 Whatman conical fluted filter paper in an ordinary conical funnel. The literature did not reveal any application of sand as a filtering media instead of filter paper.

Summary

A review of the literature has revealed the applicability of freeze-thawing to the chemical sludges selected for this investigation. The tests of specific resistance and refiltration are qualitative measurements for determining the effect of conditioning techniques such as freeze-thawing, on sludges. The purpose of this research is to detail the measurements of specific resistance and refiltration time on chemical sludges subjected to freeze-thawing with variation in the parameters of pH, solids content, and time in the frozen state.

III. EXPERIMENTAL METHODS

The intent of this research was to conduct a laboratory investigation on the effect of freeze-thaw conditioning on dewatering of selected chemical sludges. The purpose of this chapter is to describe the apparatus used, the experimental procedures employed, and the analytical techniques utilized in the work undertaken.

Sources of Sludge

The chemical sludges utilized in this research were two water treatment plant sludges, produced by separate coagulation processes using aluminum sulfate and ferric sulfate, respectively, and two advanced wastewater treatment sludges, produced by coagulation with ferric sulfate and lime, respectively.

Water Treatment Plant Sludges

Alum water treatment sludge was collected from a manhole draining the sedimentation basins of the Blacksburg-Christiansburg-V.P.I. Water Authority Plant. Sludge at this plant is collected in a storage lagoon. Table I gives a typical listing of water quality parameters of the New River and of treated water at the plant. A schematic flow diagram of the plant is shown in Figure 1 and a summary of yearly water production and use of coagulating chemicals is shown in Table II.

Ferric sulfate water treatment sludge was pumped from the bottom of the sedimentation basins of the Kingsport, Tennessee, Water Filtration Plant. Table I shows typical quality of the Holston River, as

TABLE I

TYPICAL CHEMICAL ANALYSES OF RAW AND TREATED WATER

Source	Component	Raw	Treated
New River (Blacksburg-Christiansburg-V.P.I. Water Authority)	pH	7.8	7.8
	Alkalinity M.O. (mg/l)	60	56
	Alkalinity P. (mg/l)	0	0
	Hardness (mg/l)	66	78
	Iron (mg/l)	0.01	0
	Manganese (mg/l)	0	0
	Color Units	0	0.07
	Turbidity	1.5	0
Holston River (Kingsport Water Filtration Plant)	pH	7.5	8.0
	Alkalinity M.O. (mg/l)	85	90
	Alkalinity P. (mg/l)	0	0
	Hardness (mg/l)	95	100
	Iron (mg/l)	0.15	0.05
	Manganese (mg/l)	0.02	0
	Color Units	28.3	0
	Turbidity	6	0.04

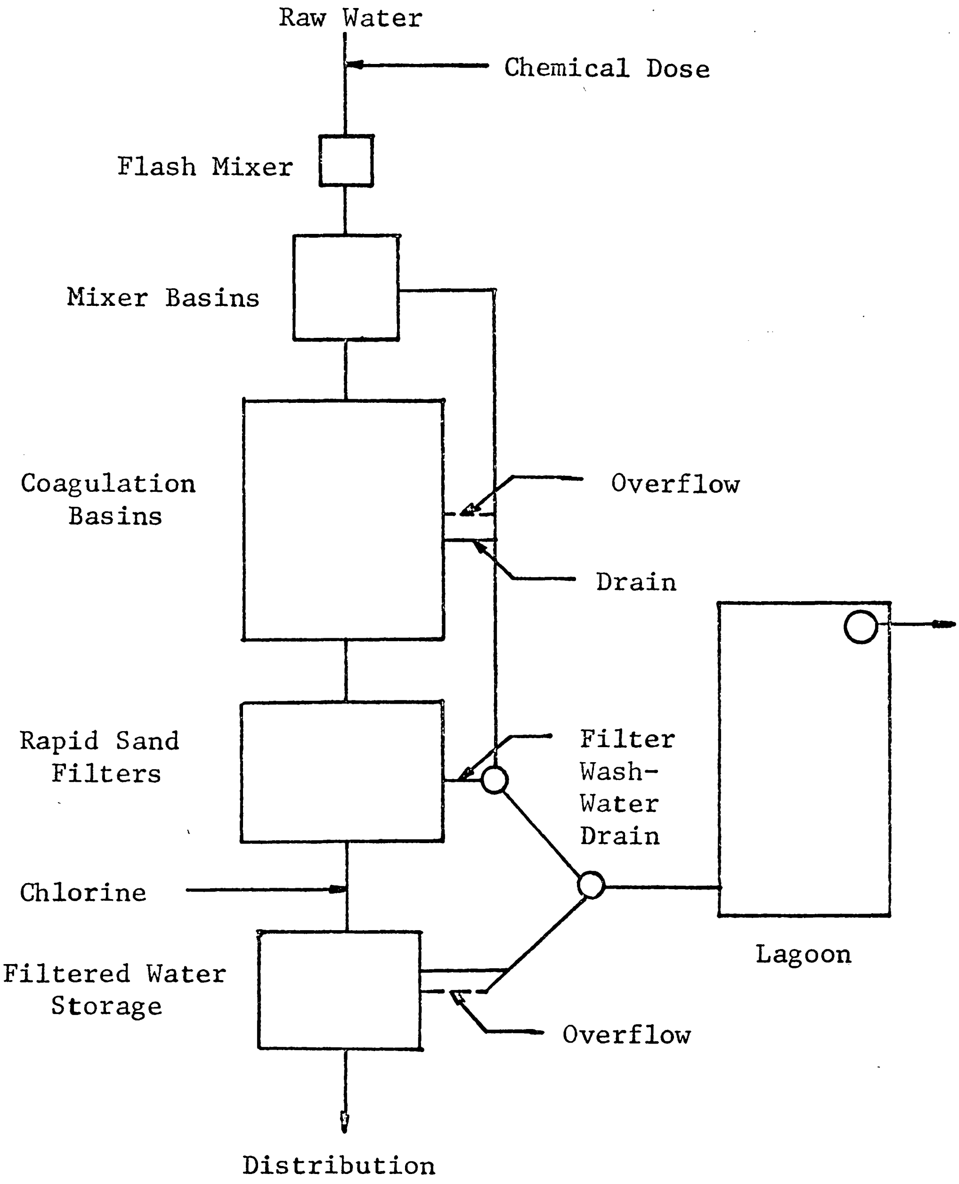

Figure 1. Flow Diagram Blacksburg-Christiansburg-V.P.I. Water Treatment Plant.

TABLE II

ANNUAL WATER PRODUCTION AND COAGULANTS

Blacksburg-Christiansburg-V.P.I. Water Authority Plant

Year	Total Water Gallons	Alum Pounds	Lime Pounds
1967	838,580,000	100,500	37,900
1968	865,997,000	104,700	39,200
1968	1,024,000,000	122,700	44,700
1970	1,061,000,000	126,300	50,800
1971	1,166,000,000	178,000	67,900
1972	1,274,000,000	184,000	75,800

Kingsport, Tennessee Water Filtration Plant

Year	Total Water Gallons	Ferric Sulfate Pounds	Lime Pounds
1967	2,405,000,000	251,000	295,000
1968	2,405,000,000	241,000	346,000
1969	2,406,000,000	280,000	422,000
1970	2,620,000,000	300,000	361,000
1971	2,624,000,000	310,000	314,000
1972	2,876,000,000	399,000	376,000

well as the characteristics of the treated water. The schematic flow diagram in Figure 1 is also typical of the Kingsport plant except for the following variations: (1) chlorination is performed in the flash mix unit; (2) slow mixing is accomplished during gravity flow through a baffled unit, as opposed to mechanical agitation; (3) both conventional and high-rate rapid sand filtration are used; and (4) sedimentation basin sludge and filter backwash water are drained by gravity to the Holston River for ultimate disposal. Yearly water production and use of coagulating chemicals are shown in Table II.

Advanced Wastewater Treatment Sludges

A lime sludge and a ferric sulfate sludge were produced from the secondary effluent of the Stroubles Creek high-rate trickling filter sewage treatment plant located in Blacksburg, Virginia. A sump pump was used to pump effluent from the secondary clarifiers into a 55 gallon drum. Lime and ferric sulfate were added until the pH, as recorded by a Fisher Model 120 pH Meter, reached 11.5 and 4.5, respectively. Jenkins (44) has determined these pH levels to be optimum for phosphorus removal at the Stroubles Creek plant which has an effluent phosphorus concentration ranging from 7 to 14 mg/1. Rapid agitation was provided manually for thirty seconds and was followed by twenty minutes of manual slow mixing. The floc was allowed to settle for twenty minutes. After the supernatant was decanted, the sludge was poured into five gallon plastic containers for further concentration.

The Stroubles Creek Sewage Treatment Plant handles domestic sewage from the Blacksburg area, including the Virginia Polytechnic Institute and State University campus, and includes some contributions from light industry. The plant has a two MGD design capacity, but normally handles from 1.7 MGD in the summer months to 3.4 MGD during school sessions. The plant is a high-rate trickling filter plant with anaerobic digesters for sludge treatment. Digester supernatant, a high phosphorus content flow, is recycled to the main treatment stream.

General Procedures

Each sludge sample was separated into five smaller samples which were used immediately or stored at 20° C for not longer than one day. The five samples were diluted with distilled water or concentrated by supernatant removal to obtain suspended solids concentrations between 20,000 mg/l and 50,000 mg/l. Four 800 ml aliquots from each of the five smaller samples were placed in cubical plastic containers and frozen in the freezer of a commercial refrigerator. Two of the 800 ml aliquots were frozen for approximately 15 minutes beyond the time required for complete freezing. The remaining two aliquots were stored in the freezer for one week. The samples were visually checked to determine when complete freezing had occurred. Thus, time in the frozen state is only an approximate measure.

The remainder of the five smaller samples was used for characterization purposes. The sludge was analyzed for pH, total and total suspended solids, total volatile and total suspended volatile solids. Specific resistance and sand filtration measurements were conducted according to the description in a future section of this chapter. Filtrate from these tests was analyzed for chemical oxygen demand, total and total suspended solids content, and pH.

The 15 minute and one week frozen samples were thawed at room temperature or in a hot water bath. Specific resistance and sand filtration studies were conducted as with the raw samples. Of the two 800 ml aliquots frozen for each time period, one was subjected to specific resistance testing and the other to sand filtration studies. Filtrates were analyzed for the same parameters as those previously noted for raw filtrate.

The only exception to this procedure was with the ferric sulfate advanced waste treatment sludge. Only two aliquots of the five raw samples were frozen. The aliquots were frozen for 24 hours and analytically tested as with the remaining three sludges.

Analytical Procedures

Solids Determinations

Raw sludge samples were analyzed for total and volatile solids and total and volatile suspended solids in accordance with the procedures outlined in Standard Methods for the Examination of Water and Wastewater, 13th edition (45). A 100 ml sample was used for total and volatile solids. A 10 ml sample was used for total and volatile suspended solids. Oven temperatures were 103° C for total solids determinations and 600° C for volatile solids determinations.

Specific resistance filtrates and sand bed filtrates and refiltrates were analyzed for total and total suspended solids. A 100 ml sample was used for determining total and total suspended solids of specific resistance filtrates. A 25 ml sample and a 50 ml sample were used for initial sand bed filtrate total suspended solids and total solids, respectively. A 100 ml sample was used for determining total and total suspended solids of the sand bed refiltrate. All determinations utilized a dry temperature of 103° C.

Samples to be tested were thoroughly mixed to assure homogeniety. Duplicates, and triplicates in the case of raw total suspended solids determinations, were analyzed to assure accuracy.

Chemical Oxygen Demand

Chemical oxygen demand was determined by the dichromate reflux method as described in Standard Methods (45). One 20 ml aliquot from each filtrate collected was used in this determination.

pH

The pH was determined by a Fisher Model 120 pH Meter. Adjustment of the pH meter was accomplished through the use of standard pH 7 buffer solution, and the electrode was cleaned with distilled water before and during use.

Specific Resistance

The Buchner funnel specific resistance test was selected as one means of measuring the filterability of the conditioned and unconditioned chemical sludges. The procedure described by Coackley and Jones (32) was used throughout this research. Specific resistance was reported in sec^2/gm.

The apparatus used is illustrated in Figure 2. The procedure consisted of placing a moistened piece of Whatman No. 42 filter paper in the bottom of a 7 cm Buchner funnel. The paper was seated to the funnel by application of distilled water and a vacuum. After seating, the vacuum was switched off to remove the distilled water from the 100 ml Mohr burette used for collected filtrate. A pinch clamp was placed on the vacuum line and the vacuum was reapplied for final adjustment by a manometer to 12 inches of mercury. A 100 ml sample of sludge was mixed well and applied to the filter paper. The pinch clamp on the vacuum line was released slowly after 10 to 15 seconds had been allowed for cake formation. A stop watch was started as the filtrate reached a zero reading level and time was noted for collecting every 5 ml of filtrate. For unconditioned samples, time was noted until 50 ml of filtrate was collected. For conditioned sludges, the time was noted until 80 ml of filtrate had been collected.

The specific resistance was calculated from the following equation:

$$r = \frac{2PA^2b}{\mu C}$$

where r = specific resistance, sec^2/gm
P = pressure differential = 12" Hg = 414.36 gm/cm^2
A = filter area = 38.47 cm^2
μ = filtrate viscosity, taken as the viscosity of water at the temperature at which the filtration test was conducted
C = average suspended solids in sample, gm/ml
b = slope of the T/V vs. V plot, sec/cm^6
where V = ml of filtrate collected in T sec.

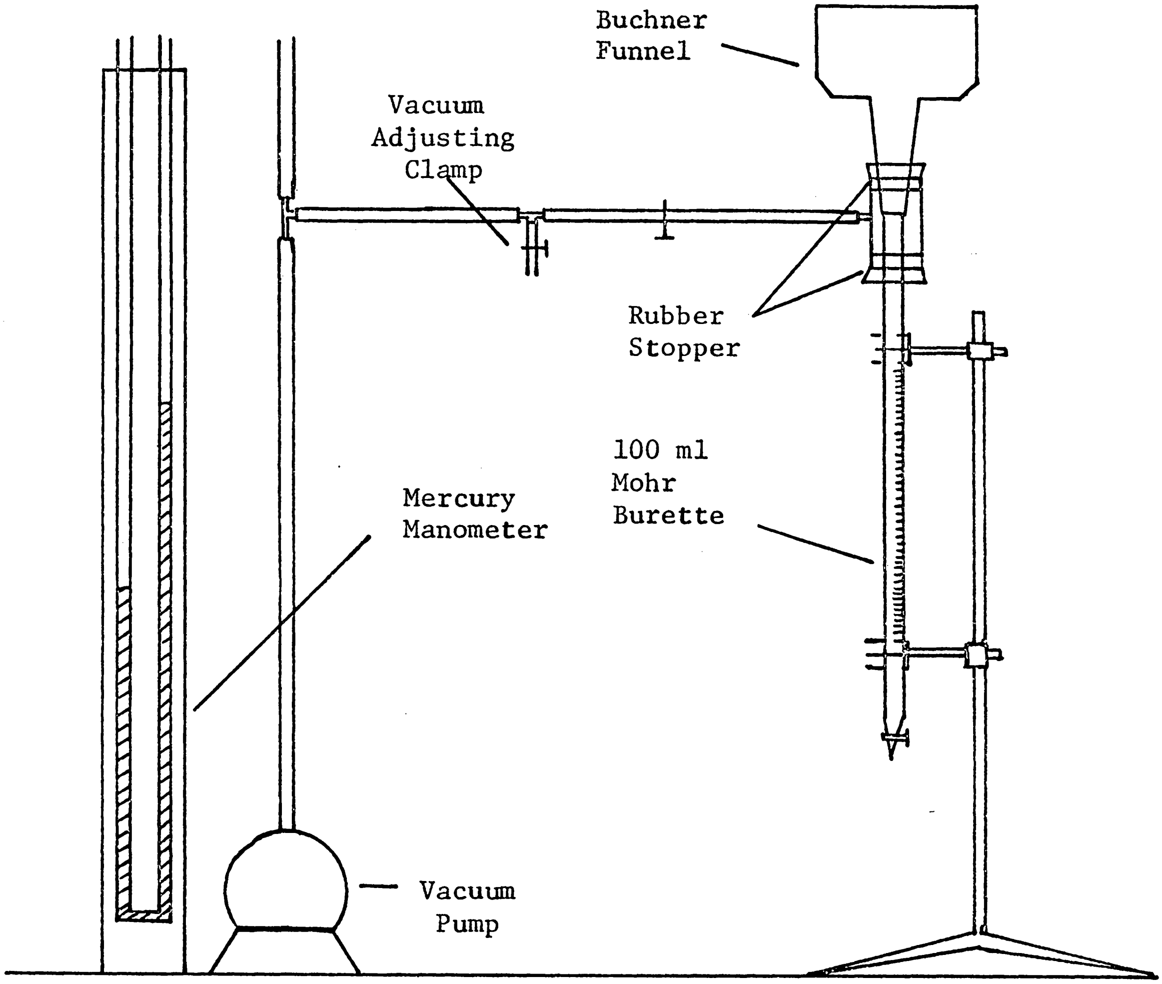

Figure 2. Buchner Funnel Assembly.

Unconditioned samples always produced a straight line on the typical T/V versus V plot used in specific resistance tests. Unconditioned samples showed a tendency not to stabilize until approximately 30 ml had been collected. From that point the plot usually resulted in an approximate straight line. Volume correction as reported by Coackley and Jones (32) was not used because it produced somewhat erratic results.

Since freeze conditioning destroyed colloidal structure and resulted in agglomeration of colloids into a relatively coarse granular structure similar to sand, some difficulty was encountered in suspending the solids for a time sufficient to obtain representative samples for specific resistance testing. To overcome this problem, conditioned samples were placed on a jar test apparatus and agitated at approximately 80 rpm. Two 100 ml aliquots were then siphoned off while agitation was in progress. Filtration times were recorded as the average of two samples, typical of the procedure of Gates and McDermott (35).

Sand Filtration and Refiltration

Gravity sand filtration was selected as a second means of measuring filterability. The particular sand filtration beds constructed and used by Parker (46) were also used for this research. The sand bed consisted of a plexiglass cylinder with an inside diameter of 2 11/16 inches and a height of 12 inches. A 1 1/2 inch column of sand was supported within the cylinder on a wire and cloth base 1 1/2 inches from the bottom. Drainage fluid was collected by a funnel attached to the bottom of the cylinder and the volume of drainage was measured in a 500 ml graduated cylinder. A diagram of the drainage cylinder is shown in Figure 3.

Before each drainage experiment, the cylinder was prepared by placing 1 1/2 inches of sand on the wire base and washing and wetting the sand by running three liters of distilled water through the bed. After the bed had been thoroughly drained, an 800 ml aliquot of the sludge samples, unconditioned or freeze conditioned, was carefully applied to the bed and the cylinders were covered to prevent evaporation. Five aliquots, representing the five different solids concentrations of each sludge, were monitored at one time. The time was recorded at the beginning of the test and readings were recorded at the 200 ml, 400 ml, and 500 ml levels. After drainage ceased, total volume of filtrate collected was recorded. A 150 ml sample of the filtrate was set aside for solids determinations and the remaining filtrate was reapplied to the top of the previously deposited filter cake. The same time sequences recorded for the initial filtration were recorded for refiltration. The refiltrate was tested for solids content, COD, and pH, as outlined previously in this chapter.

Due to the length of time required to finish the test, refiltration was performed on only one raw sample of each advanced waste treatment sludge. The sludge cakes deposited from raw samples were also tested for moisture content when gravity drainage had apparently ceased.

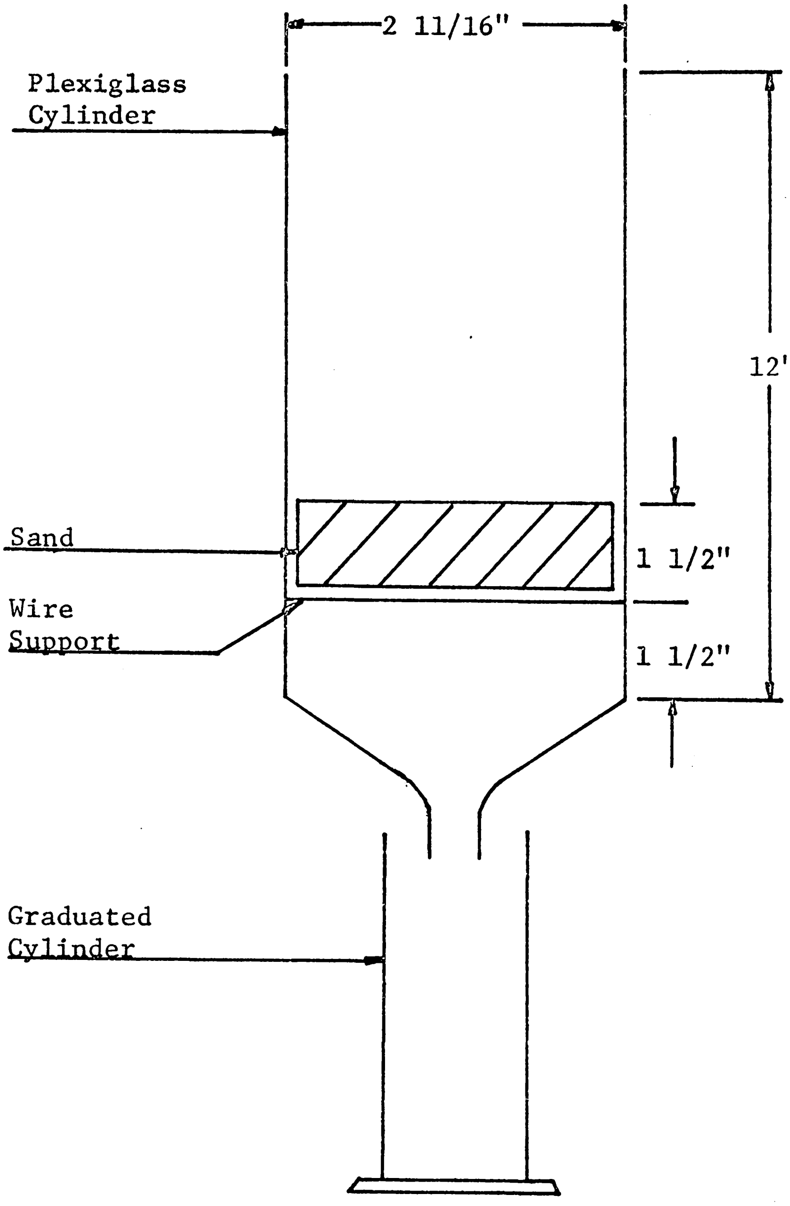

Figure 3. Sand Bed Drainage Cylinder.

All freeze conditioned samples were subjected to refiltration testing. As with specific resistance, the problem of keeping the granular particles in suspension existed in the initial filtration process. The 800 ml aliquots were agitated by stirring and immediately applied to the bed. Any particles adhering to container sides were then scraped manually into the bed. Adhesion was usually minimal.

The sand used in this experiment had an effective size of 0.310 mm and a uniformity coefficient of 3.39. Since replacing the sand after each experiment would have required large quantities, the sand was thoroughly washed to remove sludge particles and reused.

Filtration and refiltration studies were performed only once on all unconditioned or freeze conditioned samples of each chemical sludge. To duplicate filtration and refiltration testing would have required collection of large volumes of sludge at each of the sources and large laboratory storage space until the samples could be used.

IV. EXPERIMENTAL RESULTS

The effect of freeze-thaw conditioning on the dewaterability of selected chemical sludges was determined by measurement of specific resistance values and sand bed filtration and refiltration rates. The relationship between the dewaterability of freeze conditioned sludges and the solids content and time in the frozen state is defined by test results.

Sludge Characterization

Sludge characteristics can vary widely from plant to plant and even within the same plant. It is imperative for proper correlation of past and future research that all sludges be properly characterized.

The characterization results for the four chemical sludges used in this investigation are summarized in Appendix Tables A-1, A-2, A-3, and A-4. As previously described, the solids content of each sludge tested was adjusted to five separate levels. The samples were diluted or settled and decanted until suspended solids concentrations fell within the range of 20,000 mg/l to 50,000 mg/l. The greatest percentage of the total solids in a sample existed as suspended solids. The volatile portion of the total solids varied from sludge to sludge. Ferric sulfate advanced wastewater treatment (AWT) sludge had the largest volatile portion, ranging from 31.8 to 32.3 percent. This level is a reflection of the organic content in a trickling filter treatment plant effluent. The remaining sludges indicated volatile contents of 21 percent or less, a level typical of water treatment (WT) sludges. Lime AWT sludge had less volatile solids than ferric sulfate AWT sludge because of the large amounts of calcium carbonate in the precipitate.

The pH of the unconditioned water treatment sludges was slightly more acidic than the pH of raw or treated water (see Table I). This variance indicated that a small degree of biological stabilization occurred in the sedimentation basins. The pH of advanced wastewater treatment sludges was adjusted to the range normally used for coagulation purposes.

The pH of unconditioned samples of each chemical sludge was measured prior to filtration testing by the Buchner funnel and sand bed methods, and prior to freeze conditioning of 800 ml aliquots of each sludge. The pH, specific resistance values, and sand drainage rates for each sample of each unconditioned sludge are presented in Appendix Tables A-1, A-2, A-3, and A-4.

The acidic pH of ferric sulfate AWT samples ranged from 3.1 to 3.2. Alum WT sludge and ferric sulfate WT sludge had pH values of 6.2 and 7.6 to 7.8, respectively. Lime AWT sludge represented the basic pH range with values from 11.8 to 12.1. A relationship between specific resistance values of each sludge and pH was not determined. Previously, Argo (13) determined that specific resistance values increased above pH 9.6 for unconditioned lime AWT sludge. Below pH 9.6, specific resistance values were fairly constant.

Specific resistance values as measured by the Buchner funnel test indicated that unconditioned lime AWT sludge had the lowest specific resistance, that is, the best filterability, of the chemical sludges investigated. Ferric sulfate WT sludge proved to be the least filterable of the sludges tested by the Buchner funnel vacuum filtration.

Filtrate from specific resistance testing was analyzed for quality. Total and total suspended solids determinations indicated that most of the solids present were in the dissolved form. Filtrate total solids were greatest for the advanced wastewater treatment sludges and demonstrated a tendency to increase with increasing solids concentration of the unconditioned sample. The COD levels of specific resistance filtrate from AWT sludges also increased with increasing solids concentration. Filtrates from specific resistance testing of WT sludges remained essentially the same over a range of solids concentrations. Filtrate pH levels varied only slightly from the levels recorded for unconditioned samples.

Gravity sand drainage studies indicated lime AWT sludge yielded the largest drainable volume of filtrate in the least amount of time. Measurements for lime sludge were recorded in units of seconds as compared to minutes required for obtaining the same volume of filtrate for the remaining sludges. None of the three remaining sludges appeared to dewater readily. Three samples of ferric sulfate AWT sludge failed to drain 500 ml of water from an 800 ml aliquot of sludge applied to the bed. Cake moisture retention was considerably higher, ranging from 88.1 percent to 93.1 percent. The other sludges averaged almost 10 percent less moisture retained in the sludge cake. Ferric sulfate WT sludge and alum WT sludge both dewatered slowly, with ferric sulfate requiring the longer dewatering times.

Filtrate from sand drainage studies was also analyzed for quality for comparison with specific resistance filtrate. Total solids of sand filtrates generally were less than corresponding total solids of specific resistance filtrates. Suspended solids concentrations were greater for sand filtrates. The majority of total solids were still in the dissolved form. The greatest increase in suspended solids occurred with the sand filtrate of lime AWT sludge. The lime sludge sand filtrate had a suspended solids range of 57 mg/l to 78 mg/l, whereas filtrates of other sludges contained a maximum of 12 mg/l. COD levels for sand filtrates were less than those for Buchner funnel filtrate for all sludges except lime AWT sludge. The filtrates for this sludge had essentially the same chemical oxygen demand as lime sludge specific resistance filtrates.

The pH variations for sand filtrates are noted in Appendix Tables A-1, A-2, A-3, and A-4. Of particular interest is the pH of the sand filtrate of ferric sulfate AWT sludge. These values ranged from 8.7 to 8.9 as compared to 3.1 to 3.2 for untested samples. Since the sand was cleaned and reused in drainage studies, it is assumed that the sand retained buffering capacity from a previous test in which lime sludge was used.

Refiltration studies were performed on one sample of each of the advanced wastewater treatment sludges. The lime AWT sludge refiltered the fastest. The quality of the refiltrate was somewhat improved over the quality of the filtrate, especially in reference to suspended solids concentration. This improvement was offset by an increased COD value. The ferric sulfate AWT sludge showed obvious iron leaching from the deposited sludge cake. The quality of the refiltrate was substantially inferior to that of the initial filtrate. Figures 4 and 5 represent a comparison of filtration time and refiltration time for ferric sulfate and lime AWT sludges, respectively.

Effect of Suspended Solids Concentrations on Filterability of Unconditioned and Freeze Conditioned Chemical Sludges

Suspended solids concentration for each sludge sample was adjusted by dilution or decantation to a range of 20,000 mg/l to 50,000 mg/l. Portions of the unconditioned sludges were tested for specific resistance values and sand filtration and refiltration rates. The remainder of the unconditioned sludge samples was conditioned by freezing before filtration measurements were made.

The variation of specific resistance with suspended solids concentration for unconditioned samples of the four chemical sludges is illustrated in Figure 6. Alum WT sludge and ferric sulfate AWT sludge demonstrated a trend of increasing specific resistance with increasing solids concentrations. Ferric sulfate WT sludge showed a distinct tendency for increasing suspended solids concentrations to bring about

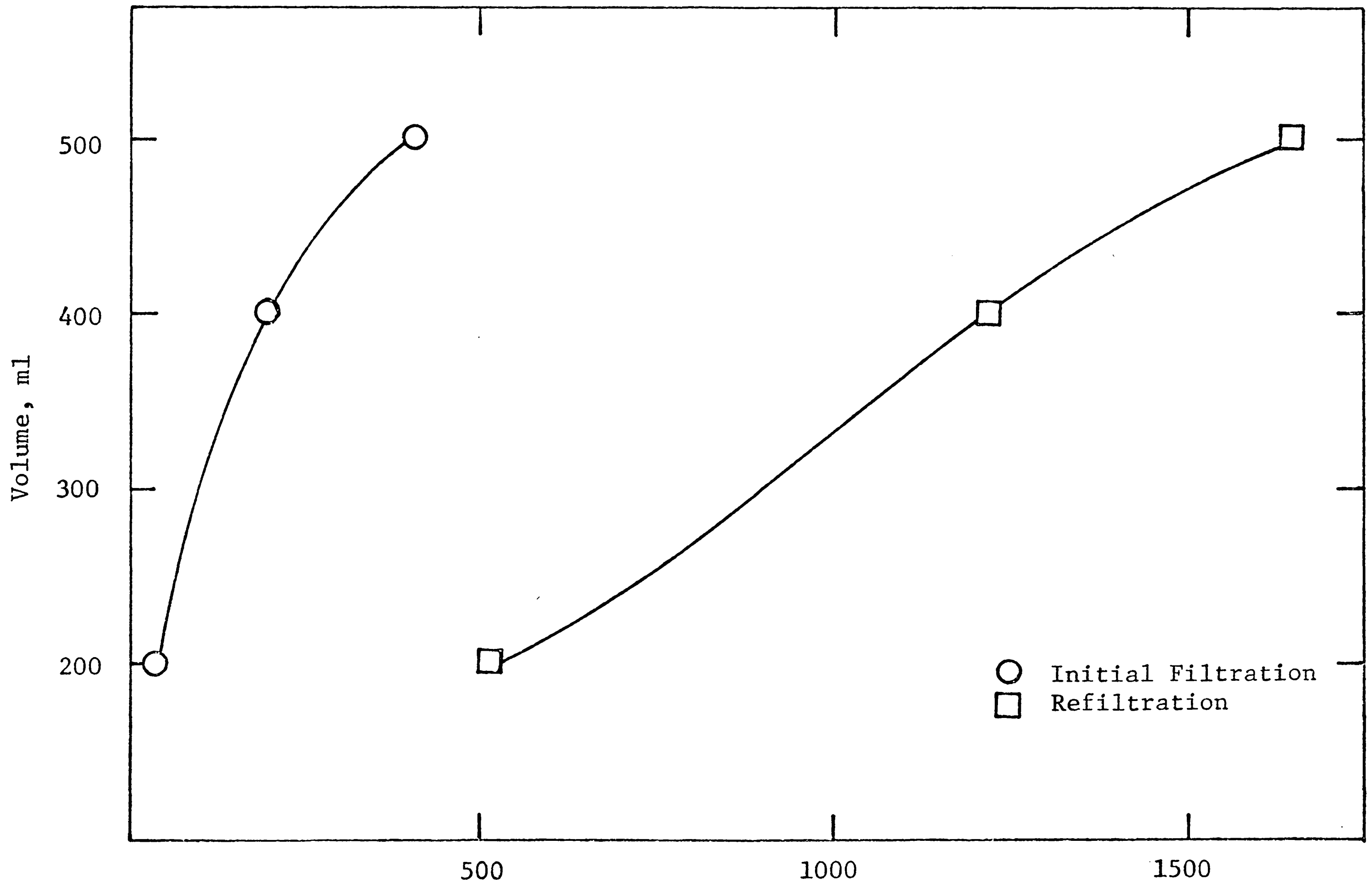

Figure 4. Comparison of Filtration Time and Refiltration Time for Unconditioned Sample of Ferric Sulfate Advanced Waste Treatment Sludge at 2.20% Suspended Solids Concentration.

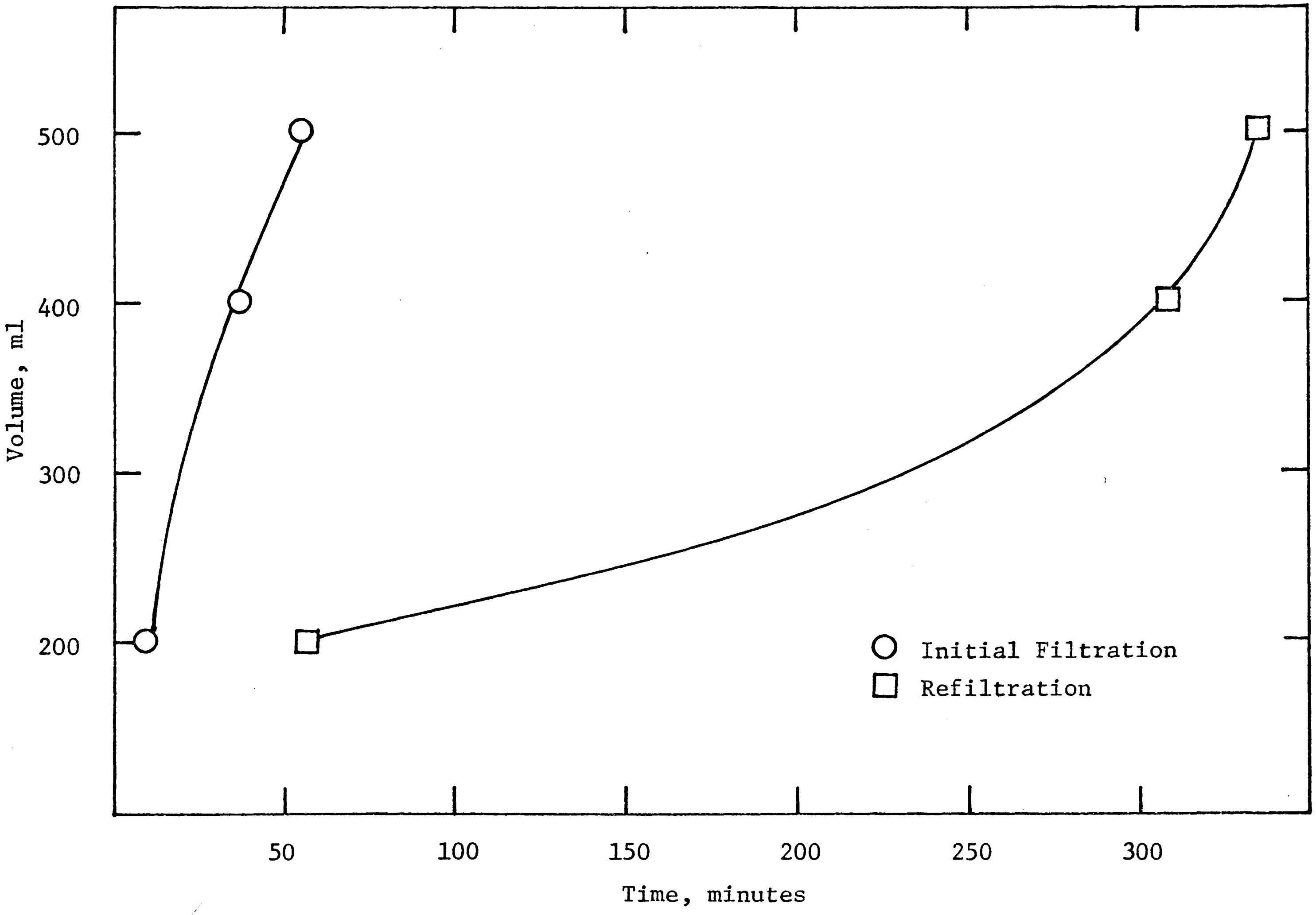

Figure 5. Comparison of Filtration Time and Refiltration Time for Unconditioned Sample of Lime Advanced Waste Treatment Sludge at 3.32% Suspended Solids Concentration.

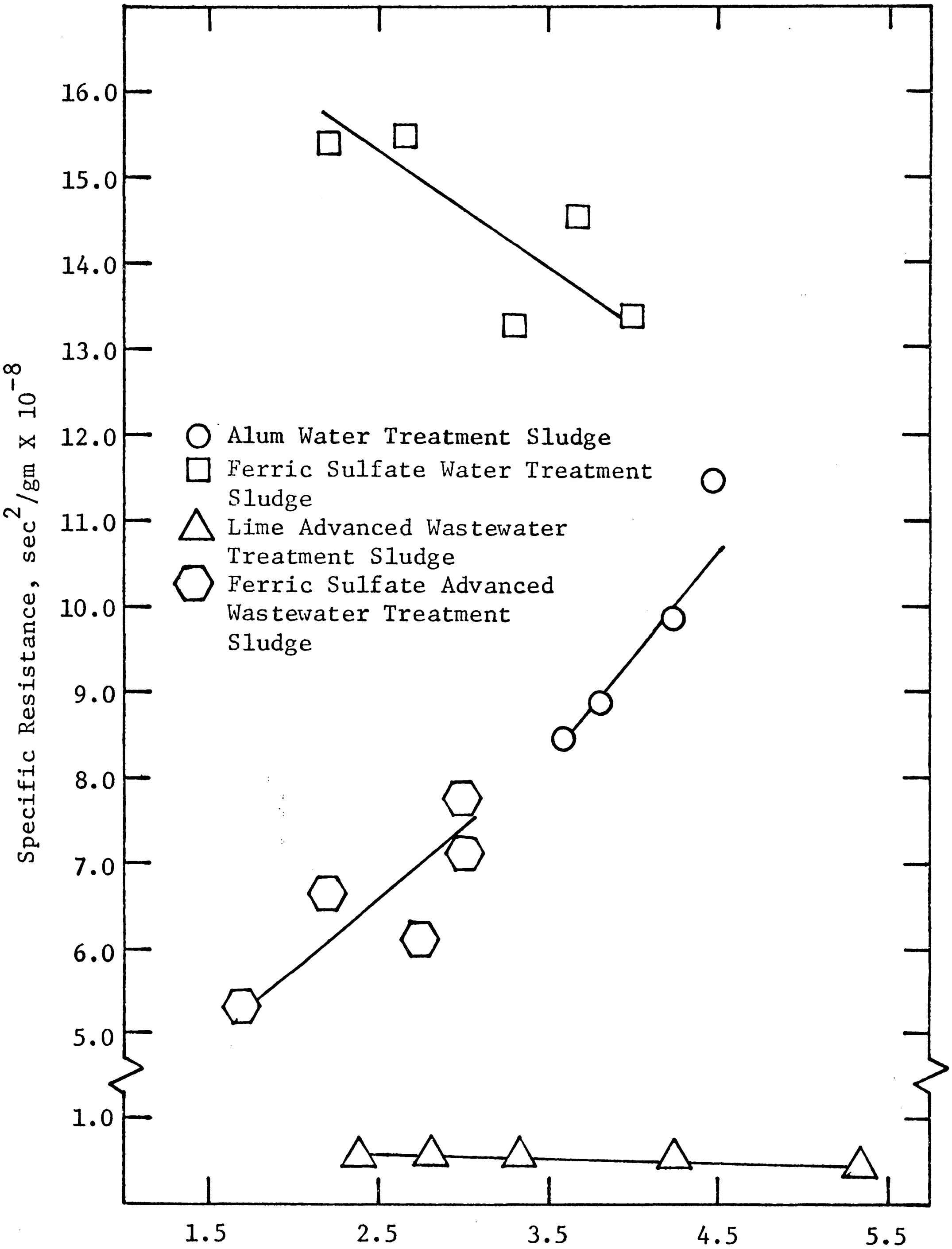

Figure 6. Effect of Suspended Solids Concentration on Specific Resistance for Various Unconditioned Chemical Sludges.

decreased specific resistance values. Lime AWT sludge filterability was affected only slightly by increasing suspended solids concentrations. Specific resistance values for this sludge decreased slightly with increasing solids content.

With the exception of ferric sulfate AWT sludge, two samples of each chemical sludge were frozen in the freezer of a commercial refrigerator. The objective was to keep one sample in the frozen state approximately fifteen minutes beyond complete freezing and the other approximately one week beyond complete freezing. Only one sample of the ferric sulfate AWT sludge was frozen. That sample was retained in the frozen state for one day.

Much difficulty was encountered in handling freeze conditioned samples for specific resistance and sand filtration and refiltration measurements. The processes of dehydration and particle agglomeration changed a gelatinous sludge into a mass of heavy granular particles which were difficult to maintain in suspension. Some measurements, especially sand drainage studies, must be considered as qualitative in nature.

The effect of increasing suspended solids concentration on specific resistance determinations for conditioned alum WT sludge is illustrated in Figure 7. Comparison of specific resistance values from Appendix Tables A-1 and A-5 indicates that freeze conditioning reduced specific resistance approximately 100 times. The fifteen minute freeze conditoned sample demonstrated the same tendency which unconditioned alum sludge did in Figure 6. Specific resistance values

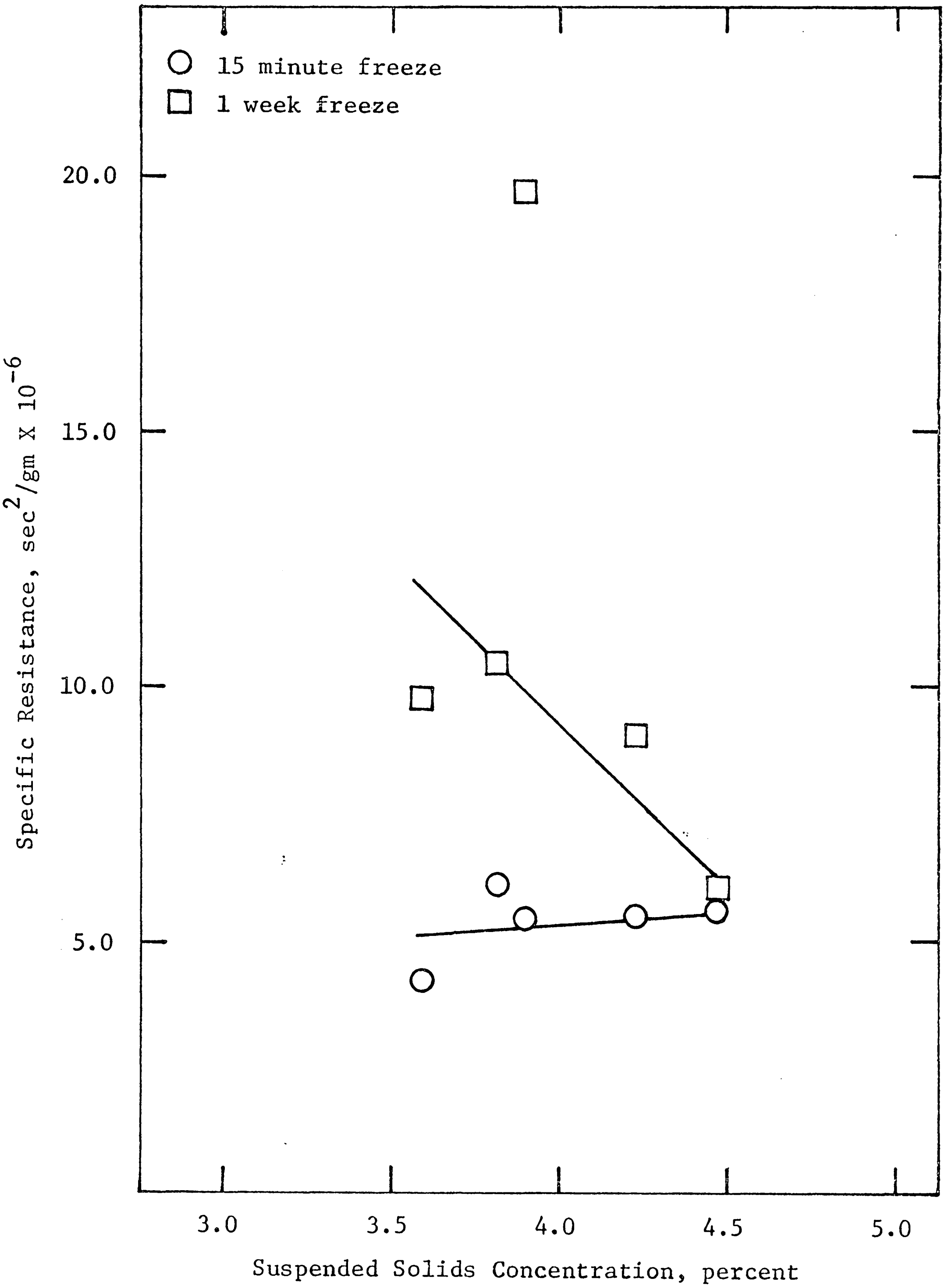

Figure 7. Effect of Suspended Solids Concentration on Specific Resistance for Freeze Conditioned Alum Water Treatment Sludge.

for the fifteen minute freeze conditioned samples increased with increasing suspended solids content. The reverse effect was true for the one week freeze conditioned sample, that is, specific resistance values decreased with increasing solids concentration. However, as noted in subsequent discussion, the specific resistance of the alum sludge conditioned for one week was higher than the fifteen minute sample. The analytical procedure for specific resistance apparently presented problems which, as discussed later, could not be overcome in this case.

Figure 8 represents the variation of specific resistance values with increasing suspended solids concentration for ferric sulfate WT sludge. Freeze conditioning reduced specific resistance values approximately 100 times. Both the fifteen minute and one week freeze conditioned samples demonstrated the tendency for specific resistance values to decrease with increasing suspended solids content. This effect is similar to that of the unconditioned samples demonstrated in Figure 6.

In an unconditioned state specific resistance values for lime AWT sludge decreased only slightly with increasing suspended solids concentration (see Figure 6). Freeze conditioning increased this tendency greatly as shown in Figure 9. Since lime AWT sludge was readily dewaterable, freeze conditioning improved filterability only approximately tenfold.

The tendency for specific resistance values to increase with increasing suspended solids concentration which ferric sulfate AWT

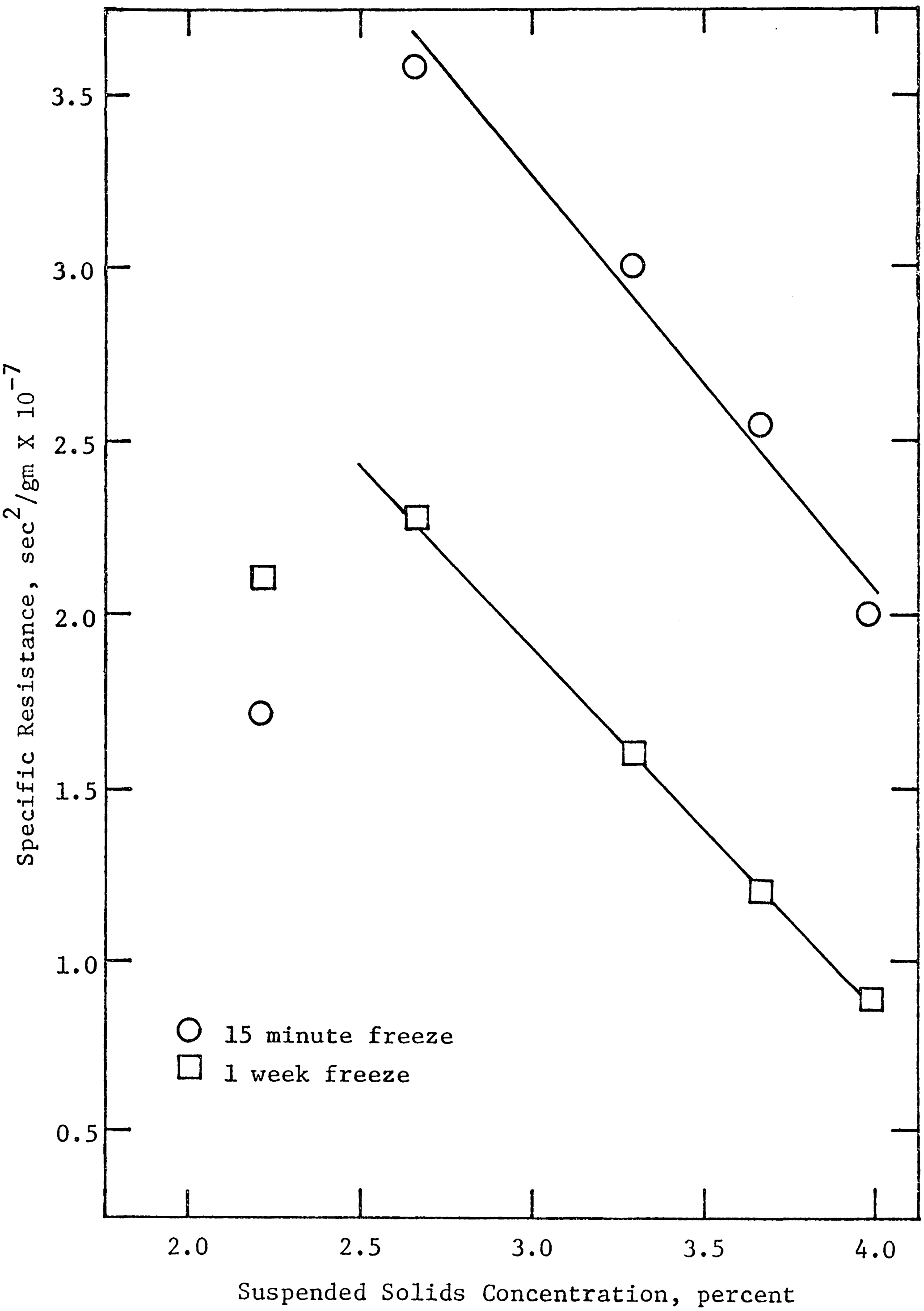

Figure 8. Effect of Suspended Solids Concentration on Specific Resistance for Freeze Conditioned Ferric Sulfate Water Treatment Sludge.

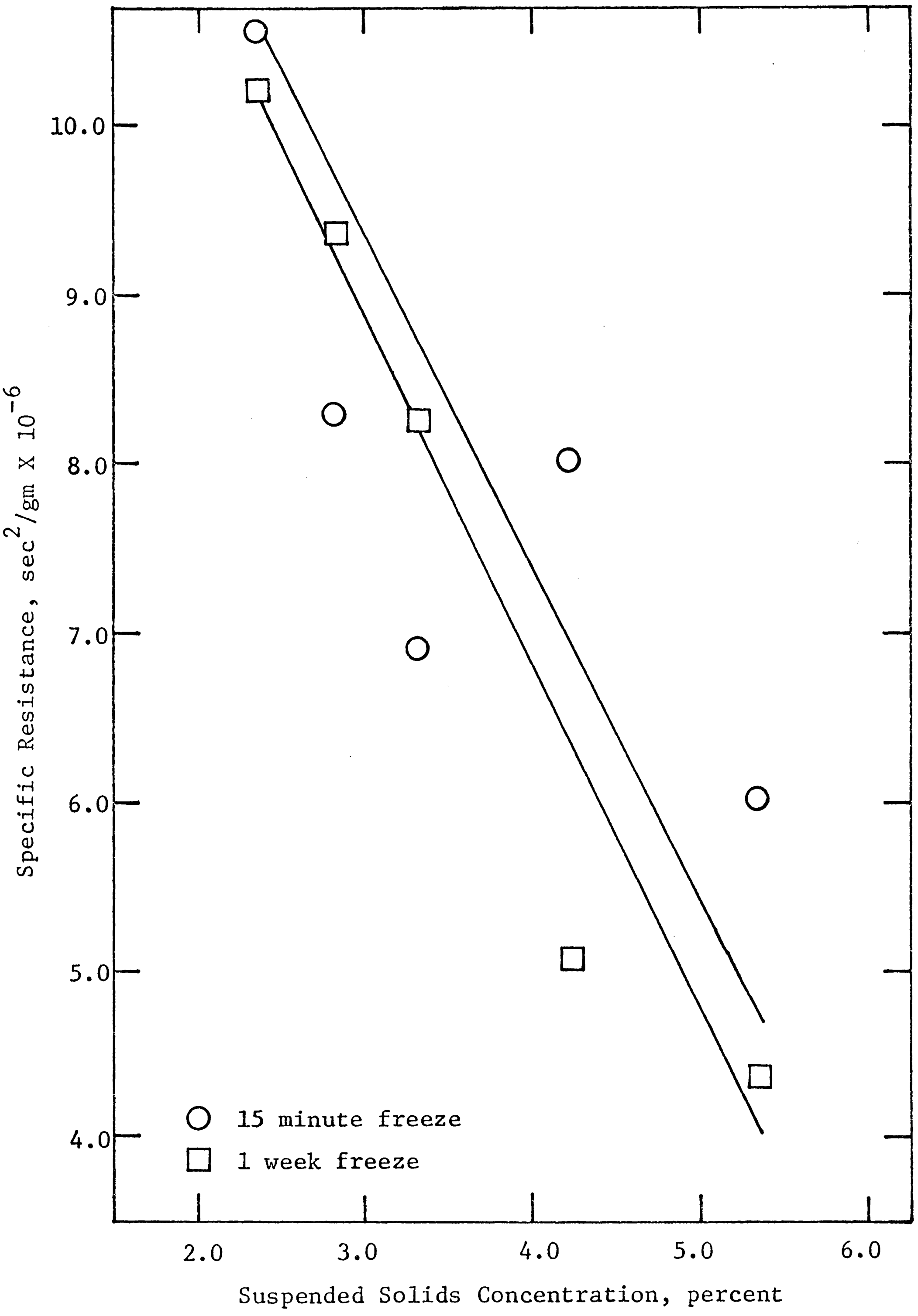

Figure 9. Effect of Suspended Solids Concentration on Specific Resistance for Freeze Conditioned Lime Advanced Wastewater Sludge.

sludge demonstrated in the unconditioned state was reversed for freeze conditioned samples. Figure 10 illustrates this reversal. As with lime AWT sludge, ferric sulfate AWT sludge experienced an approximate tenford reduction in specific resistance when freeze conditioned.

Unconditioned and conditioned sludge samples were applied to cylindrical sand drainage beds as previously described. The general tendency was for filtration and refiltration times to increase with increasing suspended solids concentrations. Freeze conditioning dramatically improved drainage times for all chemical sludges investigated. The effect of freeze conditioning was least pronounced for lime AWT sludge which was readily dewaterable in the unconditioned state.

As stated previously, difficulty was encountered in trying to keep solids in suspension for gravity sand drainage studies. Samples were agitated just prior to application to the sand bed. Agitated samples were carefully applied to the sand bed to prevent bed disturbance. Any solids which adhered to the beaker walls were scraped on to the sand bed. Filtrate was refiltered through the deposited sludge cake after a portion had been tested for total and total suspended solids concentration.

Filtration and refiltration rates for unconditioned and freeze conditioned samples of alum WT sludge are presented in Appendix Tables A-1 and A-5, respectively. Unconditioned samples demonstrated a tendency for filtration rate to increase with increasing suspended solids concentration with one exception. Freeze conditioned alum

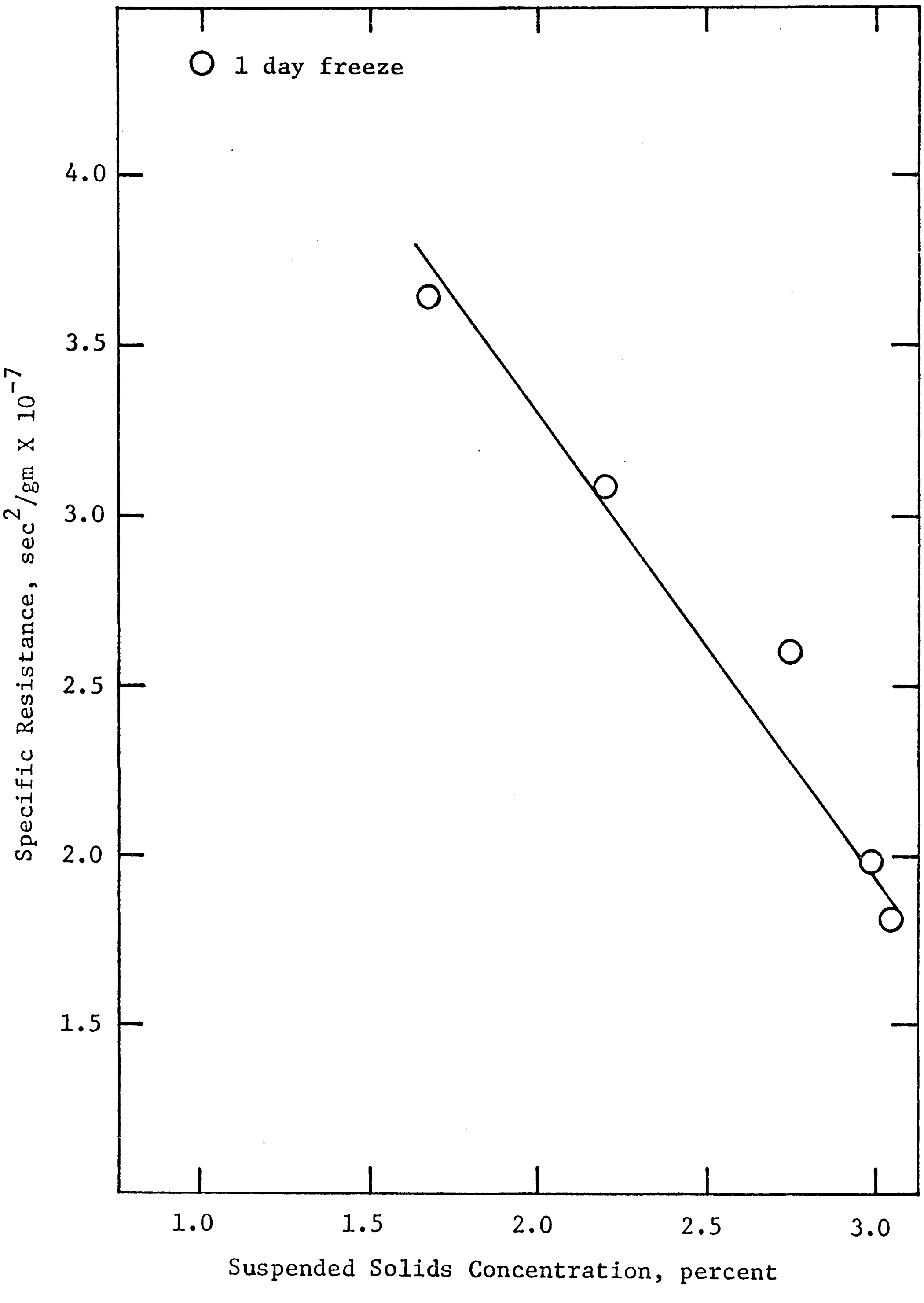

Figure 10. Effect of Suspended Solids Concentration on Specific Resistance for Freeze Conditioned Ferric Sulfate Advanced Wastewater Treatment Sludge.

samples had filtration rates so fast that only a general tendency for filtration rate to increase with increasing solids content can be noted. The dramatic effect of freeze conditioning is demonstrated when considering that a 3.58 percent solids sample which required 75 minutes to drain 200 ml of filtrate required only six seconds to drain the same volume from a freeze conditioned sample. Refiltration rates also demonstrated a tendency to increase with increasing suspended solids concentration. A comparison of freeze conditioned filtration rates and refiltration rates is given in Figure 11. The two rates are very similar for suspended solids concentrations of 3.59 percent and 4.47 percent.

Filtration rates for unconditioned samples of ferric sulfate WT sludge, as shown in Appendix Table A-2, were very dependent on solids concentration. Unconditioned filtration patterns are illustrated in Figure 12. Freeze conditioning improved dewaterability of ferric sulfate WT sludge comparable to the data previously shown for conditioned alum sludge. A comparison of filtration and refiltration rates of freeze conditioned samples indicated that there is a tendency for these rates to vary with solids content. The relationship is illustrated in Figure 13 and itemized in Appendix Table A-6.

Filtration rates for unconditioned lime AWT sludge were the best of the raw sludges investigated as shown in Appendix Table A-4. Figure 14 details the relationship between filtration time and suspended solids concentration. Filtration times did not vary predictably with increasing suspended solids concentration. Lime sludges are partly

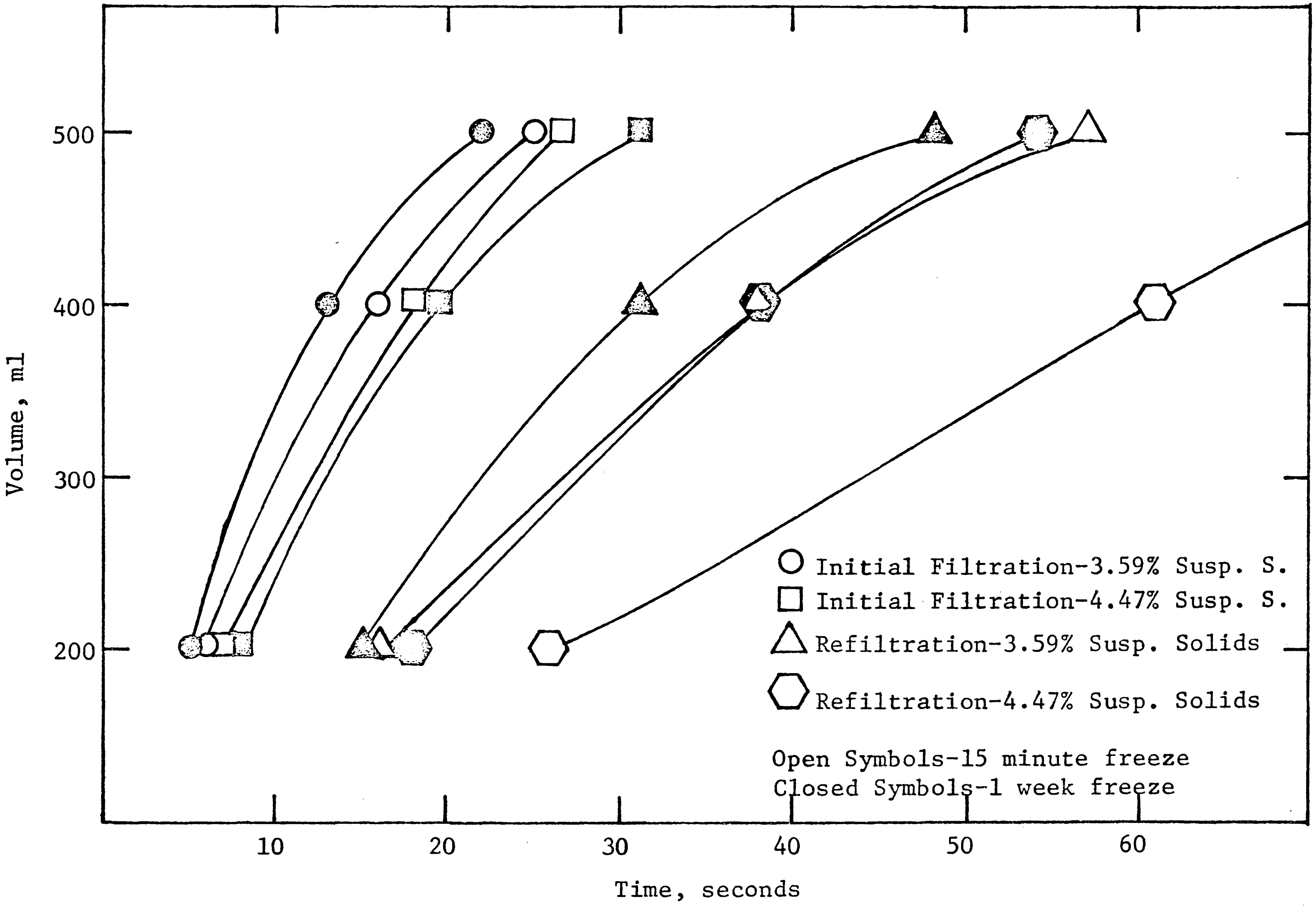

Figure 11. Comparison of Filtration and Refiltration Times for Freeze Conditioned Alum Water Treatment Sludge.

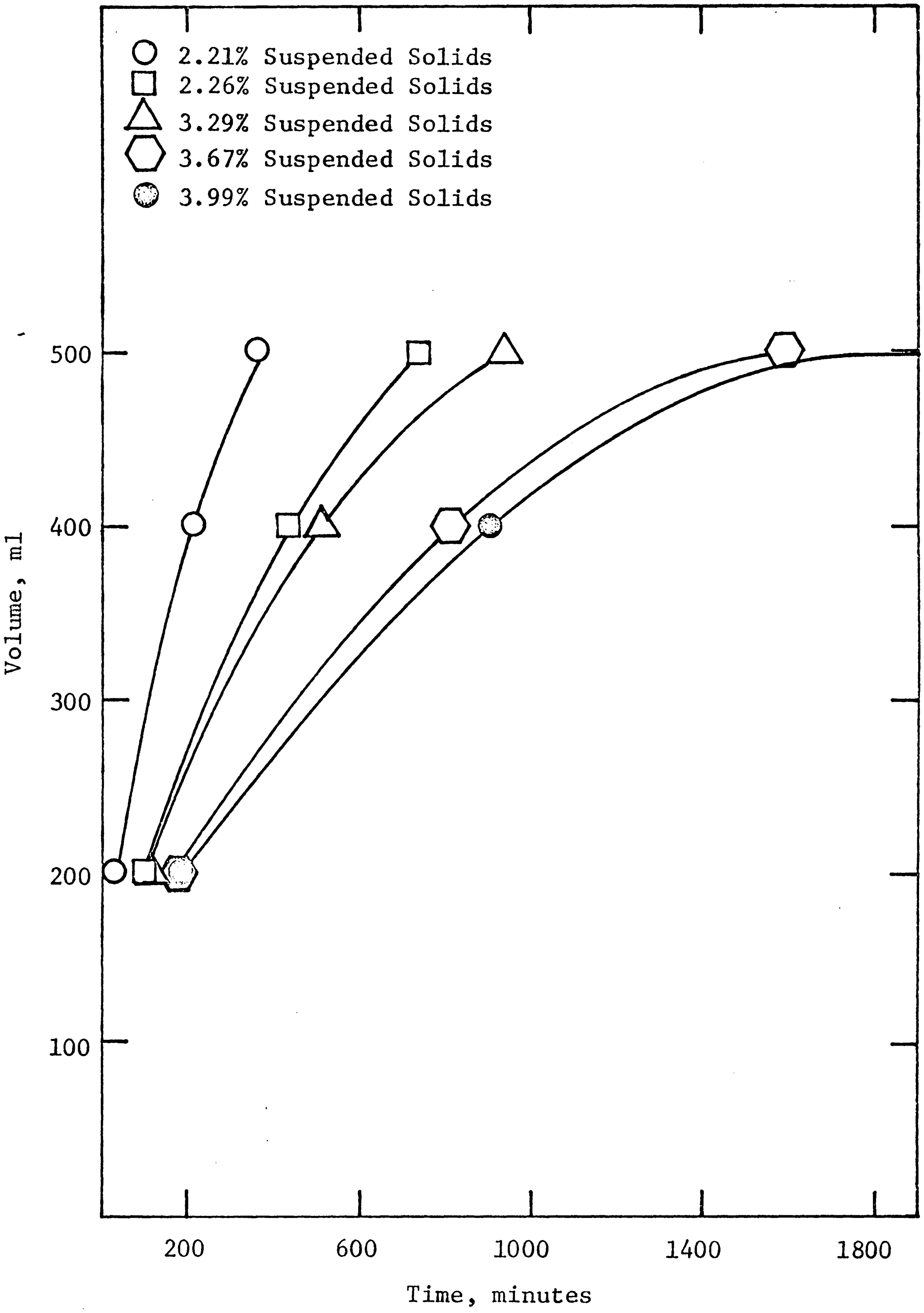

Figure 12. Effect of Suspended Solids Concentration on Filtration Times for Unconditioned Ferric Sulfate Water Treatment Sludge.

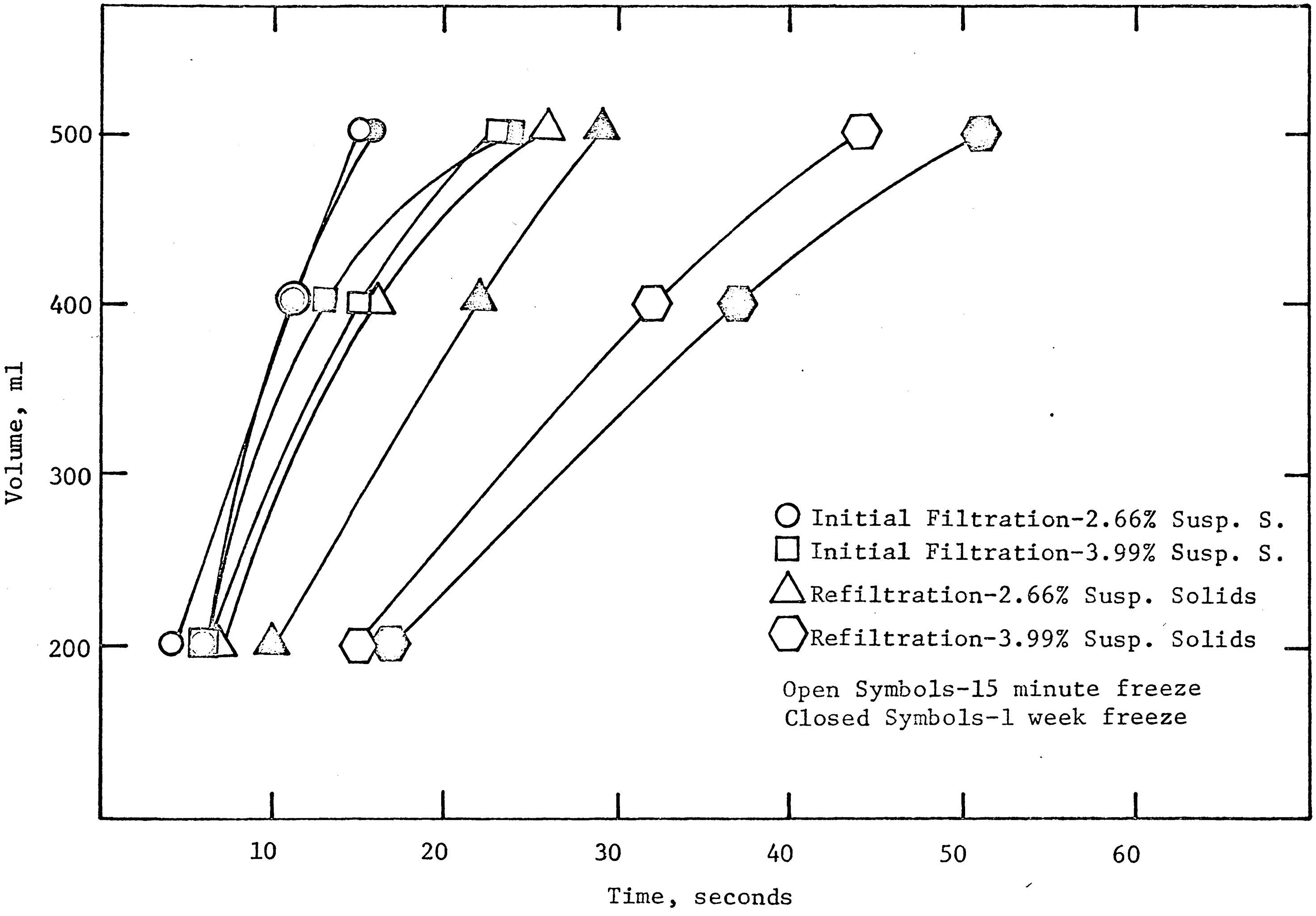

Figure 13. Comparison of Filtration and Refiltration Times for Freeze Conditioned Ferric Sulfate Water Treatment Sludge.

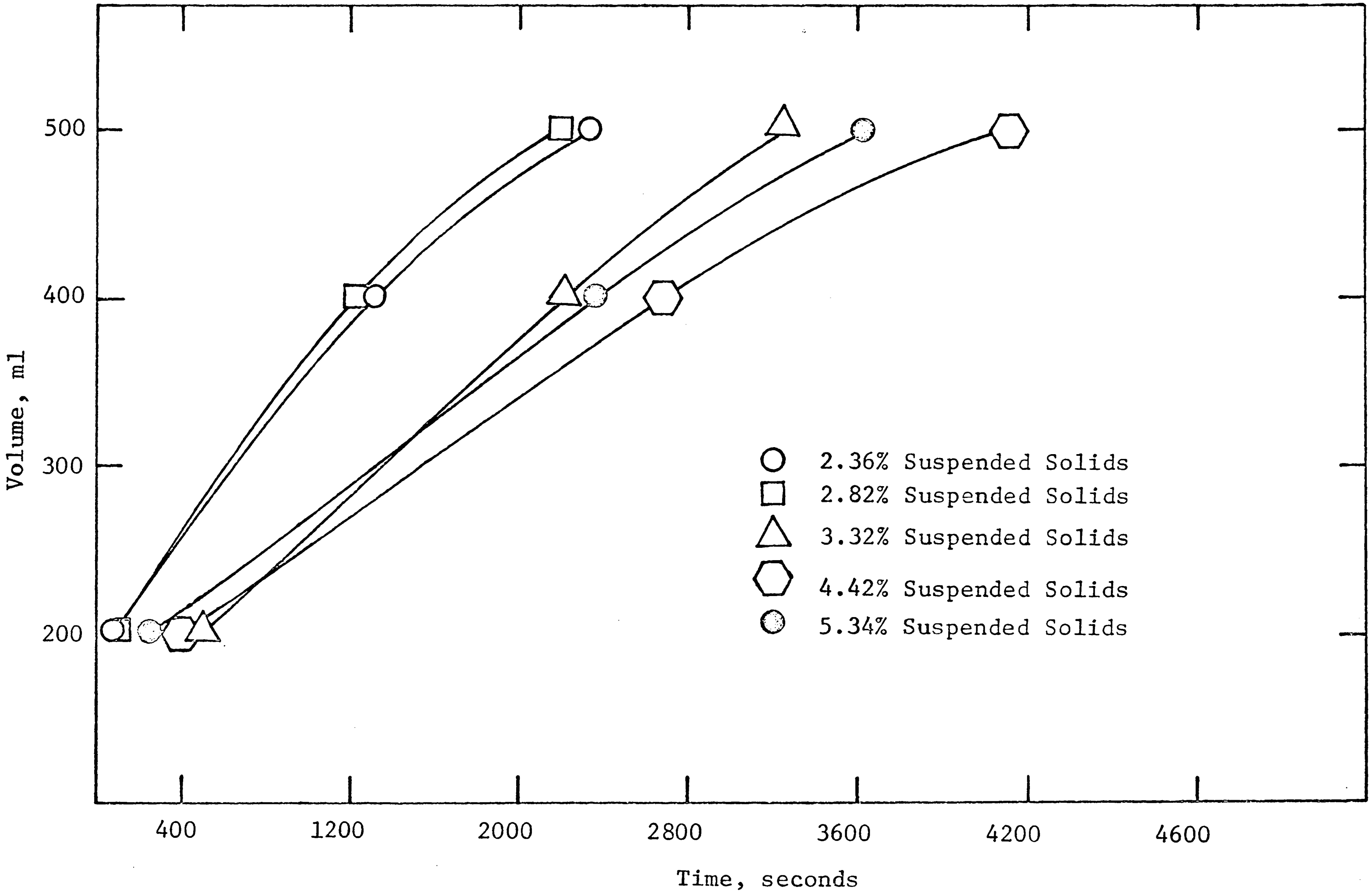

Figure 14. Effect of Suspended Solids Concentration on Filtration Times for Lime Advanced Wastewater Treatment Sludge

composed of the heavy and easily dewatered precipitant, calcium carbonate. With increasing suspended solids concentration, particles tend to interfere with the settling of other particles. This effect may either enchance or inhibit the settling process. Refiltration of the 3.32 percent suspended solids sample resulted in a very slow refiltration time as noted in Appendix Table A-4. Appendix Table A-7 contains results of testing freeze conditioned samples of lime AWT sludge. Freeze conditioned samples also demonstrated the erratic tendency with respect to solids concentration previously noted for unconditioned samples. Comparison of filtration and refiltration times is illustrated in Figure 15. Conditioning reduced filtration and refiltration times, although this effect was reduced because unconditioned samples dewatered so readily.

Unconditioned ferric sulfate AWT sludge filtration times are presented in Appendix Table A-4. Experimental results indicated that filtration times were dependent on suspended solids concentrations. As can be seen from the table, the unconditioned samples dewatered poorly. The suspended solids and filtration time relationship is illustrated in Figure 16. Freeze conditioning improved dewaterability but not to the extent which occurred with the other sludges. Freeze conditioned samples displayed the erratic solids-filtration time relationship which lime AWT sludge displayed. This trend can be seen when comparing the results tabulated in Appendix Table A-8. Filtration and refiltration times for conditioned samples are compared in Figure 17.

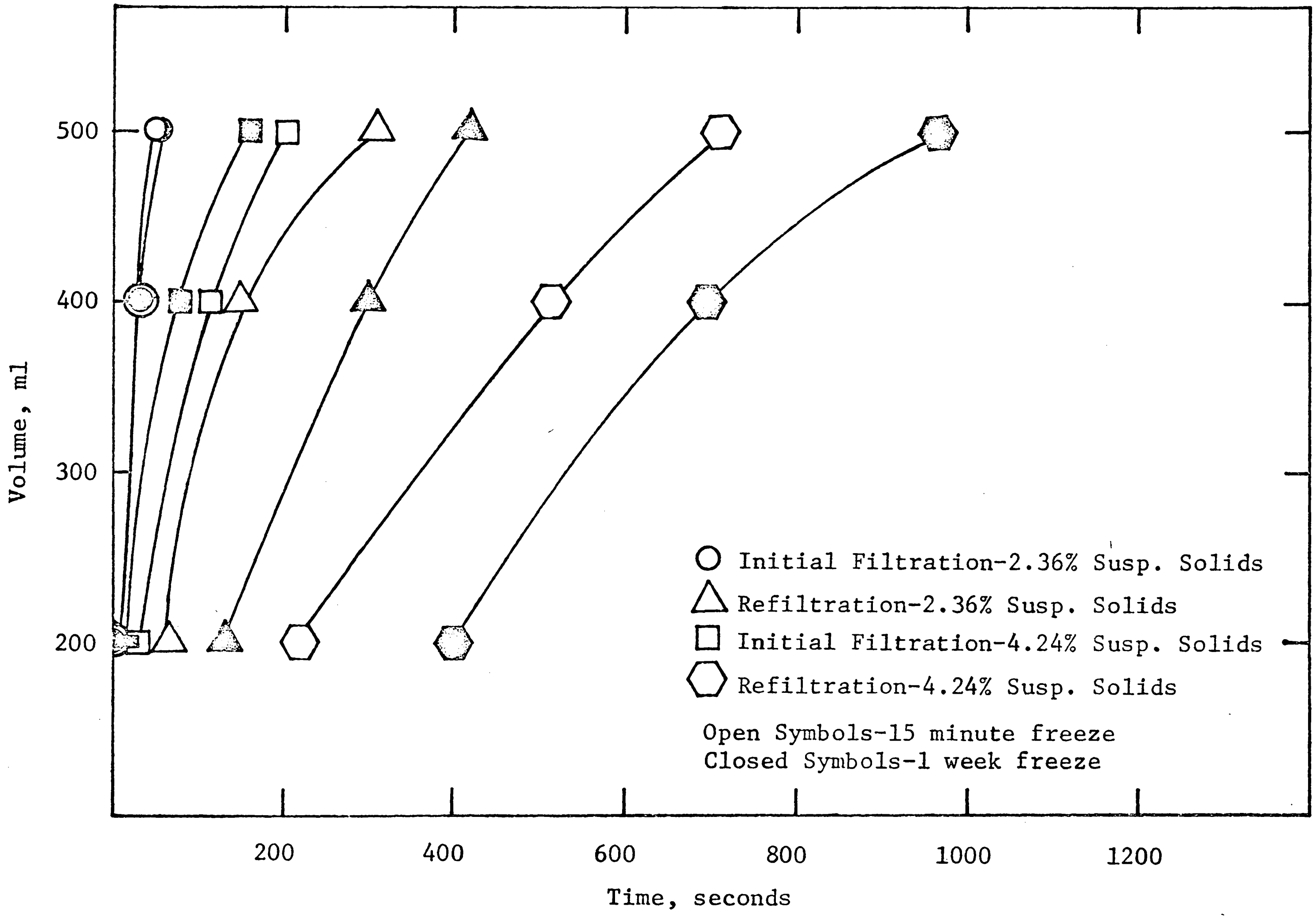

Figure 15. Comparison of Filtration and Refiltration Times for Freeze Conditioned Lime Advanced Wastewater Treatment Sludge.

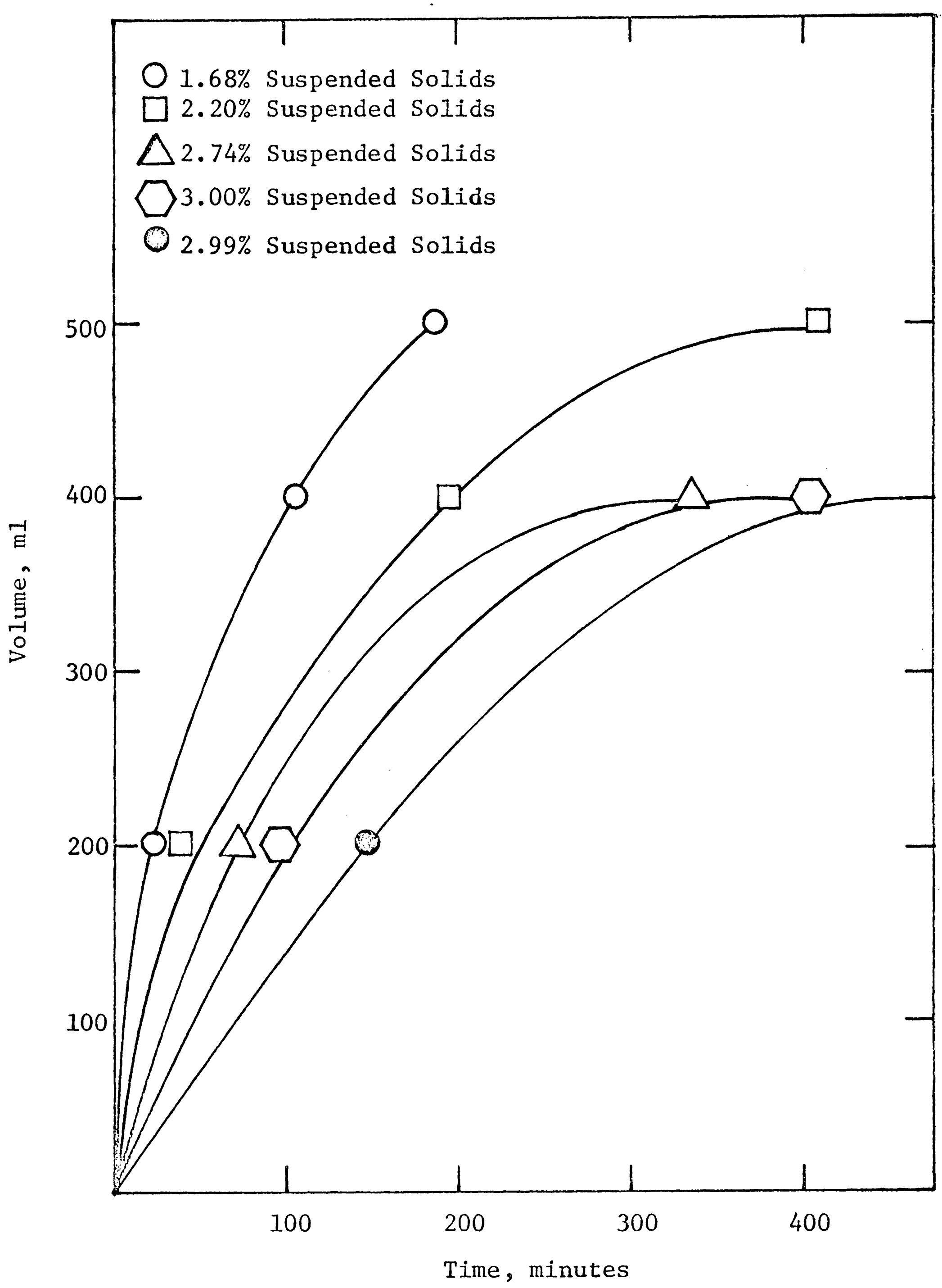

Figure 16. Effect of Suspended Solids Concentration on Filtration Time for Unconditioned Ferric Sulfate Advanced Wastewater Treatment Sludge.

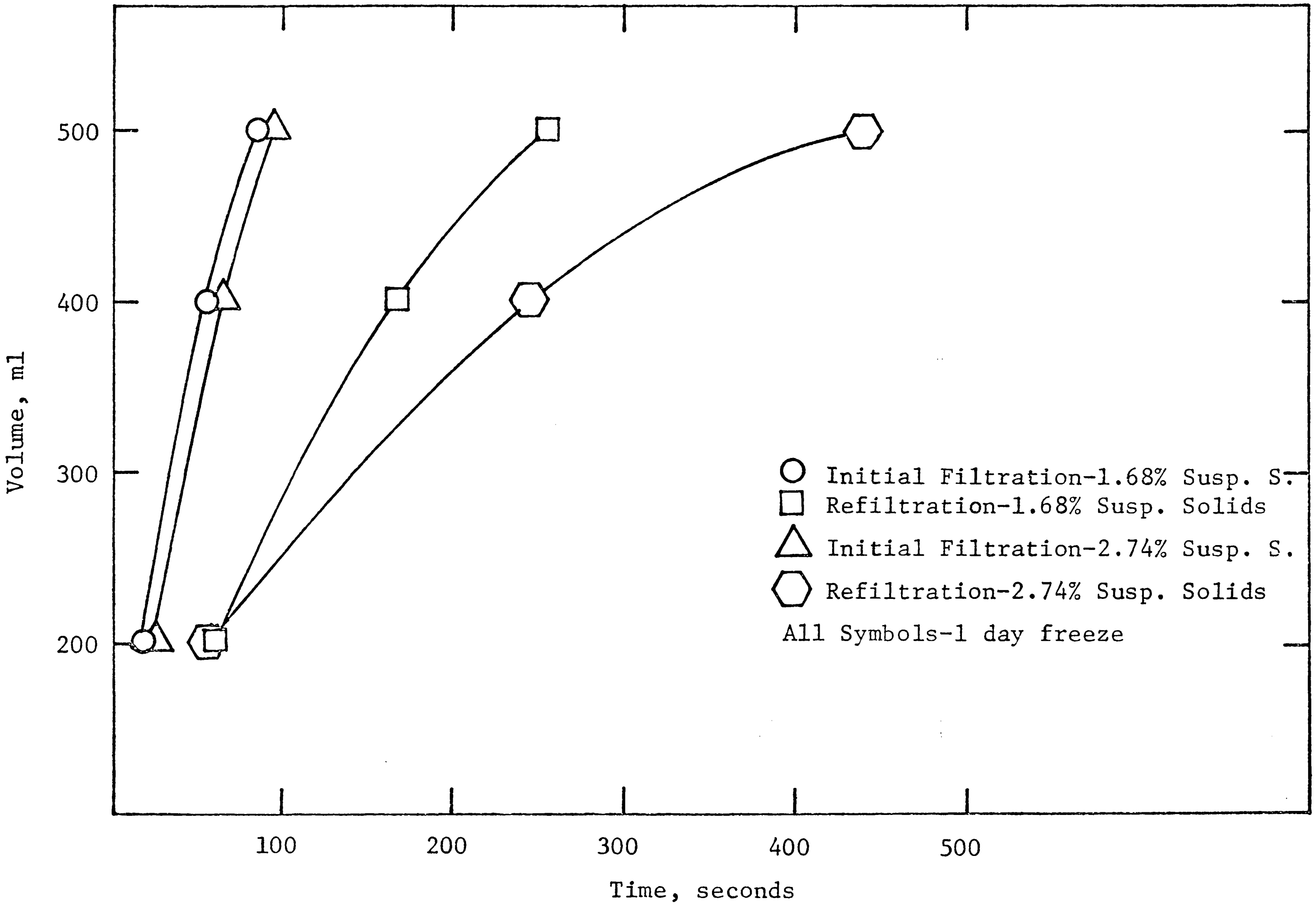

Figure 17. Comparison of Filtration and Refiltration Times for Freeze Conditioned Ferric Sulfate Advanced Wastewater Treatment Sludge.

Effect of Time in the Frozen State on Filterability of Freeze Conditioned Chemical Sludges

Alum WT sludge, ferric sulfate WT sludge, and lime AWT sludge were subjected to testing to determine the effect of time in the frozen state on filterability. The freezing procedure has been described in a previous chapter. Four 800 ml aliquots were frozen, two for approximately fifteen minutes beyond the time required for complete freezing and the other two for approximately one week. Samples were checked visually to determine when complete freezing had taken place. One 800 ml aliquot from each time period was subjected to Buchner funnel specific resistance testing. The other 800 ml aliquot was tested by gravity filtration and refiltration through a sand bed. Results of freeze conditioned testing are included in Appendix Tables A-5, A-6, and A-7.

Figure 7 incorporates a comparison of specific resistance values and suspended solids concentrations with the effect of time in the frozen state for alum WT sludge. For each suspended solids concentration investigated, the one week freeze conditioned samples gave specific resistance values higher than the fifteen minute freeze conditioned samples. This result indicated that dewaterability supposedly decreased with the increased time in the frozen state. However, filtration times for the two freeze conditioned samples actually did not vary significantly. For some samples the one week freeze conditioned sludge drained the same volume of filtrate at a faster rate than the than the fifteen minute sample. The reverse was also true in some cases. The maximum variation in drainage time was only nine seconds. Refiltration studies clearly indicated that one week freeze conditioned samples drained a given volume of filtrate faster than fifteen minute freeze conditioned samples. Comparison of filtration and refiltration times are illustrated in Figure 11.

Reference to Figure 8 indicates that for ferric sulfate WT sludge, one week freeze conditioned samples had lower specific resistance values than fifteen minute samples for each suspended solids concentration tested. Dewaterability increased with the longer retention in the frozen state. Filtration times for the two freeze conditioned samples were essentially the same, the largest variation being two seconds. Results fluctuated to such an extent that selection of the better draining sample was not possible (see Appendix Table A-6). Refiltration studies indicated that the fifteen minute freeze conditioned sample refiltered a certain volume of filtrate faster than the one week samples. This tendency is illustrated in Figure 13.

Figure 9 presents the relationship between the fifteen minute and one week freeze conditioned lime AWT samples giving specific resistance values for these samples. This plot also indicated that the one week freeze conditioned sample dewatered more rapidly than the fifteen minute freeze conditioned sample. Gravity filtration studies indicated that wide fluctuation existed from sample to sample. Three of the five samples tested indicated that the fifteen minute freeze conditioned aliquot drained faster than the one week freeze conditioned aliquot (see Appendix Table A-7). Fluctuation also existed in refiltration studies. Generally, the fifteen minute freeze conditioned sample had refiltration tendencies superior to the one week freeze conditioned sample. This trend is illustrated in Figure 15.

Filtrate Quality

Buchner funnel and sand drainage filtrates from freeze conditioned samples were tested for comparative quality. The characteristics measured are summarized in Appendix Tables A-5, A-6, A-7, and A-8.

Comparison of fifteen minute and one week freeze conditioned samples for alum WT sludge indicated no unusual variation in filtrate solids concentration from sample to sample. Gravity sand filtrate had high total and total suspended solids concentrations due to escape of solids through the beds. In each case, refiltration reduced solids to levels attainable by Buchner funnel filtration. COD levels of Buchner funnel filtrate and sand bed refiltrate were comparable.

Comparison of data for ferric sulfate WT sludge indicated the filtrate for the one week freeze conditioned samples was generally superior to the fifteen minute freeze conditioned samples. Total and total suspended solids were less but COD levels were higher for one week freeze conditioned samples. This result indicated that as longer freezing times dehydrated a particle more soluble oxygen demanding material was also extracted.

Buchner funnel filtrates for lime AWT sludge had high dissolved solids concentrations but were low in suspended solids. The one week freeze conditioned sample had lower quantities of suspended matter indicating agglomeration of particles was enhanced by longer freezing times. Sand filtration and refiltration removed more of the dissolved solids, reducing total solids concentrations. COD levels were higher for sand refiltrates than Buchner funnel filtrates.

Comparison of Buchner funnel filtrate with sand refiltrate for ferric sulfate AWT sludge indicated that the two were comparable for one day freeze conditioned samples. Sand refiltrate had larger total solids concentrations, a result probably of iron leaching from the deposited cake. Suspended solids concentrations were essentially the same for the two filtrates.

V. DISCUSSION OF RESULTS

The purpose of this investigation was to furnish technical information concerning freeze-thaw conditioning of four selected chemical sludges. The results aid in understanding the effect of freeze conditioning on sludge dewatering properties. The following analysis points out those results considered particularly significant and seeks to interpret them in terms of application to current practice.

Sludge Characterization

The importance of proper sludge characterization cannot be over emphasized. Since sludge can dramatically vary from plant to plant, and even within a plant, proper characterization is mandatory for correlation purposes.

The characteristics of water treatment sludges and wastewater treatment sludges are completely different. The pH of water treatment sludge was adjusted in the coagulation process of each water treatment plant by lime addition. The pH of sludge samples varied slightly, generally on the acidic side, from the pH of untreated or treated water. This result indicates that a certain amount of biological degradation had occurred while the sludge was stored in the sedimentation basins. The pH of the wastewater sludges was a result of attempting to coagulate in the pH ranges for phosphorus removal as determined by Jenkins (44). These ranges were 4.5 to 5.0 for ferric sulfate and 11.0 to 11.5 for lime. The pH results indicated that some excess coagulant was added in each case. Excess coagulant would result in greater quantites of hydroxide precipitate, affecting the drainability of the sludges.

Solids content was adjusted by dilution or concentration to obtain a range which would indicate the effect of suspended solids concentration on Buchner funnel specific resistance values and gravity sand filtration and refiltration rates. Volatile portions were comparable to those determined by past researchers. Alum WT sludge used in this investigation contained from 20.7 to 21.1 percent volatile solids compared to 22.1 to 31.7 percent as recorded by Bugg (33). Ferric sulfate WT sludge contained a volatile portion from 15.4 to 16.6 percent. Olver (34), investigating ferric sulfate WT sludge, reported a volatile solids range of 20.1 to 20.7 percent of total solids. The volatile portion of lime AWT sludge ranged from 17.0 to 17.6 percent, compared to 15 percent obtained by Argo (13). Ferric sulfate AWT sludge contained the largest volatile portion, from 31.8 to 32.3 percent. This result indicates that lime AWT sludge was substantially affected by precipitation of calcium carbonate while ferric sulfate AWT sludge contained relatively more organic compounds, perhaps due to the relatively lower dose of coagulant required.

Specific resistance values were comparable to those reported in the literature. Alum WT sludge specific resistance values ranged from 8.45×10^8 sec^2/gm to 11.45×10^8 sec^2/gm for suspended solids concentrations ranging from 3.59 percent to 4.47 percent. Gates and McDermott (35) reported a specific resistance of 20.7×10^8 sec^2/gm for a 4.1 percent solids concentration. Ferric sulfate WT sludge specific resistance ranged from 13.2 X 10^8 sec^2/gm to 15.5 X 10^8 sec^2/gm. This range was not uniform over the suspended solids range of 2.21 percent to 3.99 percent. Olver (34) reported a specific resistance of 50 X 10^8 sec^2/gm for a 3.6 percent solids sample. Olver worked with a ferric sulfate sludge from a plant utilizing activated carbon addition. Lime AWT sludge had a specific resistance range from 0.45 X 10^8 sec^2/gm to 0.58 X 10^8 sec^2/gm over a solids range from 2.36 percent to 5.34 percent. These values varied somewhat with the measured value of 1.25 X 10^8 sec^2/gm at 4.3 percent solids reported by Argo (13). This difference was probably the result of excess coagulant addition in the present study and the subsequent formation of more calcium carbonate and calcium hydroxide. Ferric sulfate AWT sludge had better drainability characteristics than its water treatment counterpart, perhaps due to the nature of the wastewater being treated. Specific resistance values ranged from 5.32 X 10^8 sec^2/gm to 7.74 X 10^8 sec^2/gm for 1.68 percent to 2.99 percent solids samples.

Gravity sand filtration and refiltration studies also indicated that unconditioned lime AWT sludge exhibited the best filterability of the sludges investigated. Time measurements of volume collection were made in units of seconds compared to units of minutes for the other sludges. The remaining sludges were gelatinous in consistency, whereas the lime sludge was granular. Both ferric sulfate sludges had very poor dewaterability on sand beds. Ferric sulfate WT sludge required long times to dewater. Ferric sulfate AWT sludge retained water in the sludge cake. Alum WT sludge drained only marginally faster than the ferric sulfate sludges. The gelatinous consistency of the hydrates of aluminum and iron released water very slowly when compared to the granular nature of the lime sludge.

Freeze Conditioning of Chemical Sludges

Freeze conditioning greatly improved the dewatering characteristics of all chemical sludges investigated as illustrated in Figures 18, 19, 20, 21, 22, 23, 24, and 25. The most dramatically affected were the gelatinous sludges. The consistency of gelatinous sludges was irreversibly changed to that of sand. The processes of particle dehydration and agglomeration due to the subsequent increase in surface tension greatly reduced the volume occupied by solids. The heavy granular nature of the solids in freeze conditioned sludges made the task of keeping the solids in suspension for testing difficult.

There are many operational variables which affect freeze conditioning of chemical sludges. This research investigated the effects of solids content and time in the frozen state on the drainability of freeze conditioned chemical sludges. The effect was measured in terms of filterability changes as determined by Buchner funnel specific resistance testing and sand drainage studies.

The pH of sludge is believed to be unimportant with regard to the effect of freeze conditioning, an important aspect when considering the wide range of pH values for chemical sludges investigated in this report. This statement would appear logical when the mechanism of

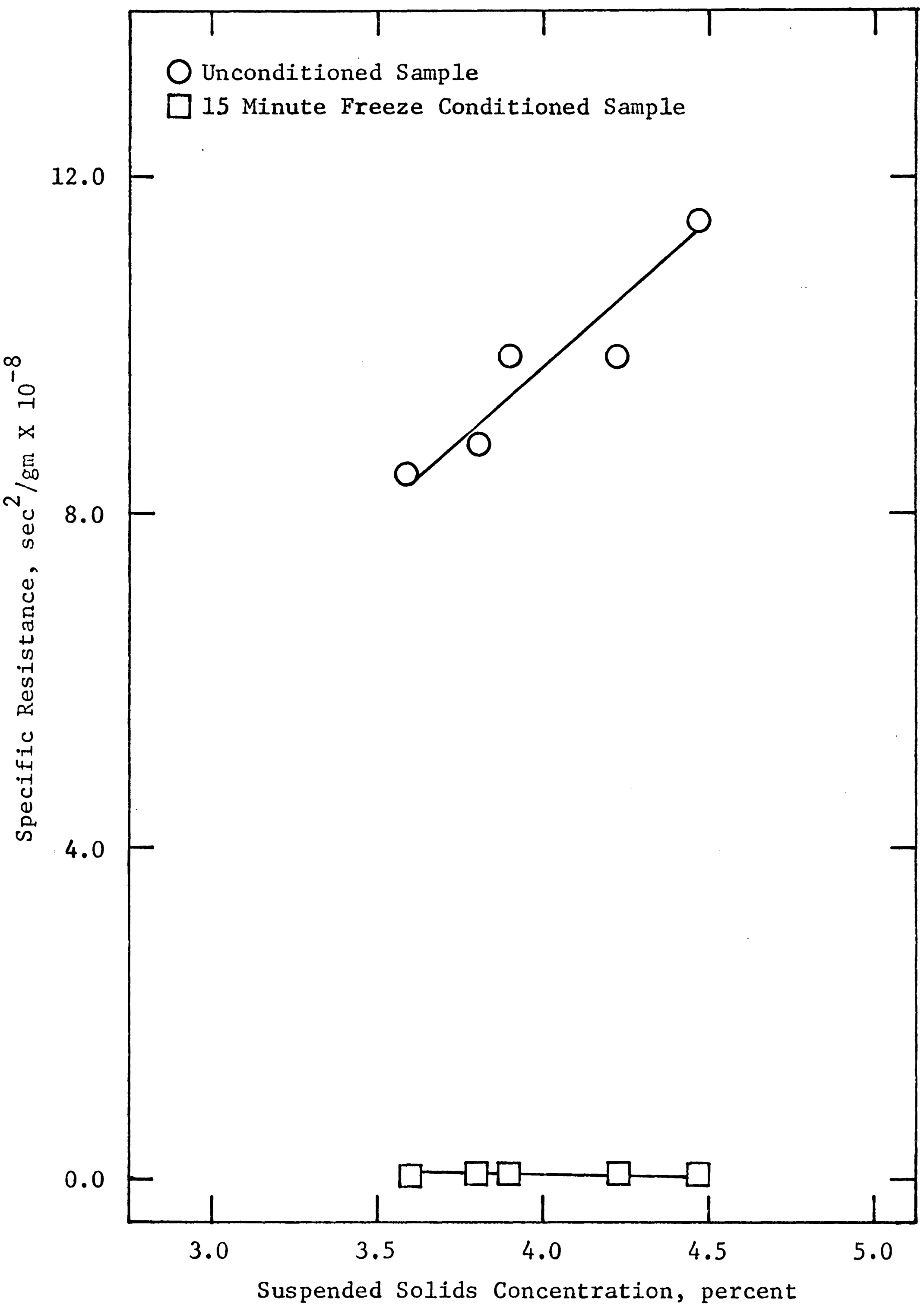

Figure 18. Comparison of Specific Resistance for Unconditioned and 15 Minute Freeze Conditioned Alum Water Treatment Sludge.

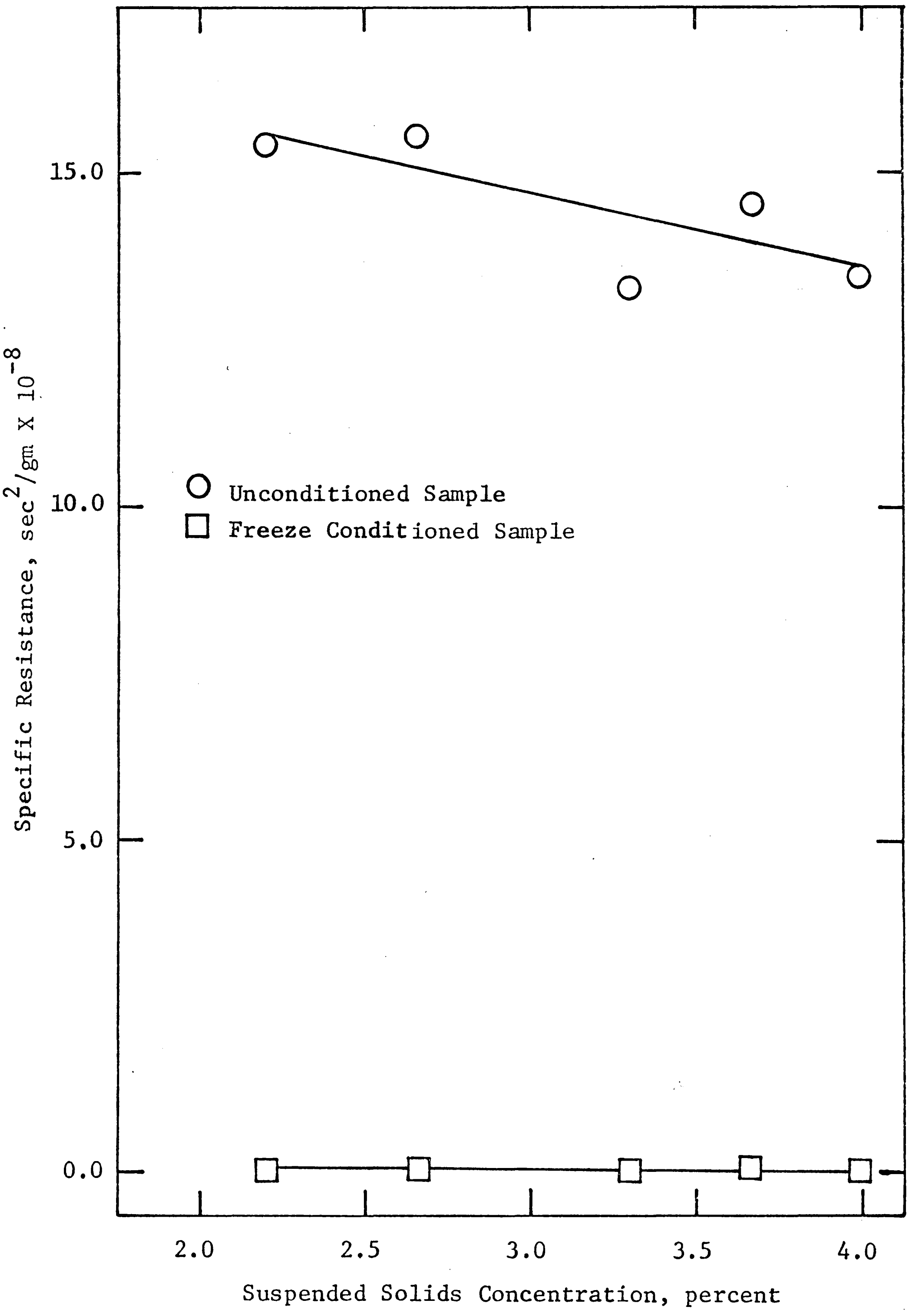

Figure 19. Comparison of Specific Resistance for Unconditioned and 15 Minute Freeze Conditioned Ferric Sulfate Water Treatment Sludge.

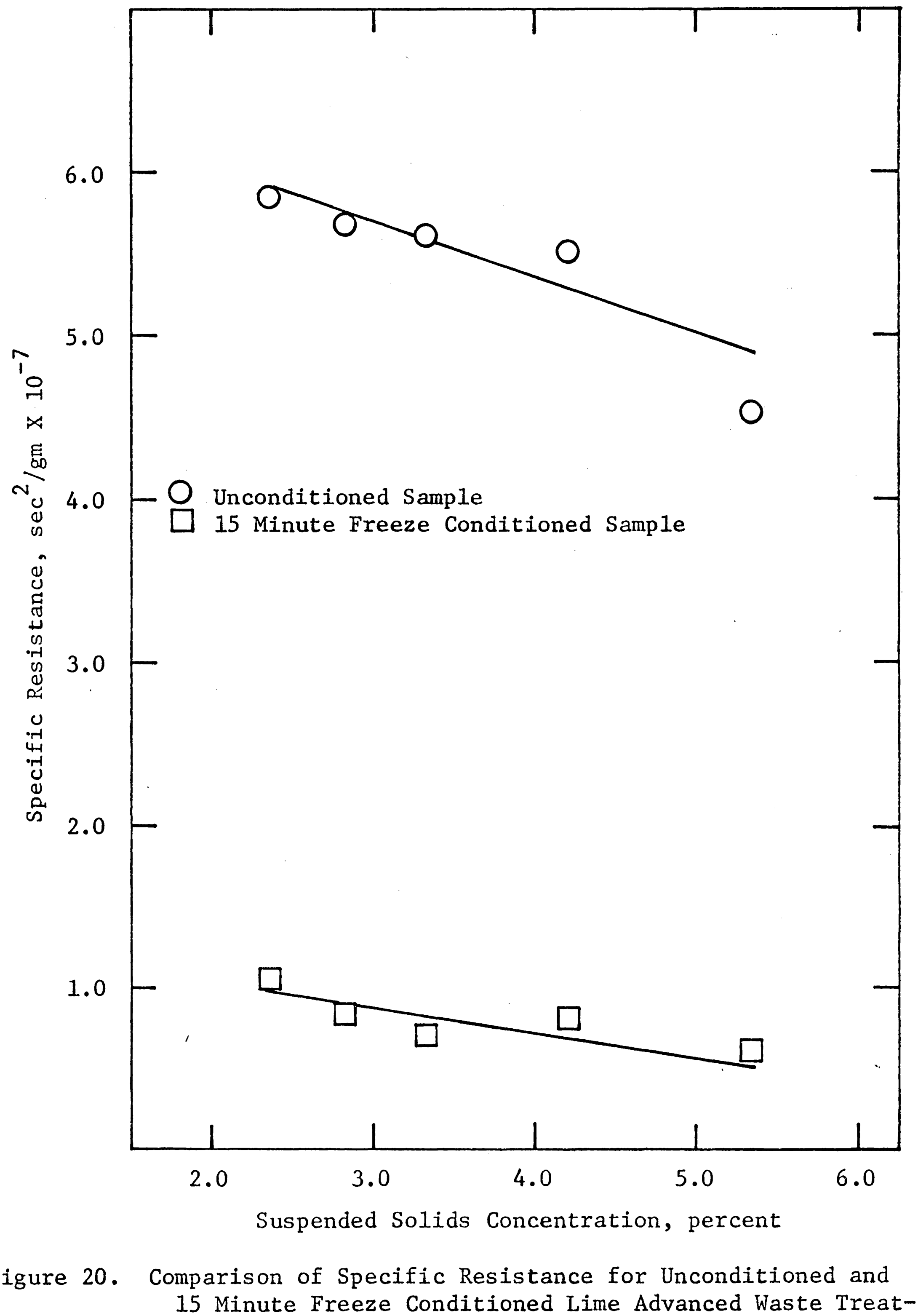

Figure 20. Comparison of Specific Resistance for Unconditioned and 15 Minute Freeze Conditioned Lime Advanced Waste Treatment Sludge.

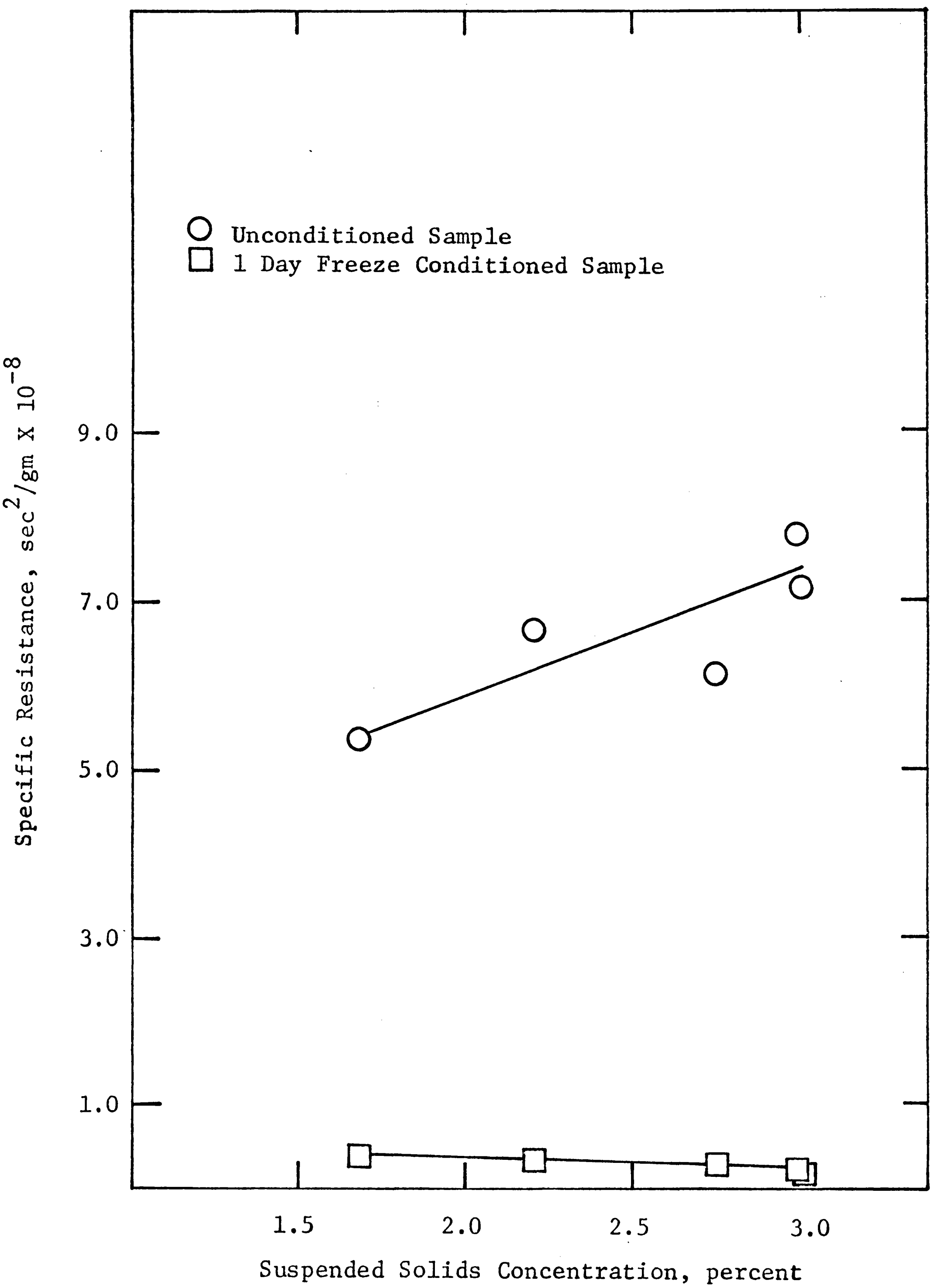

Figure 21. Comparison of Specific Resistance for Unconditioned and 1 Day Freeze Conditioned Ferric Sulfate Advanced Waste Treatment Sludge.

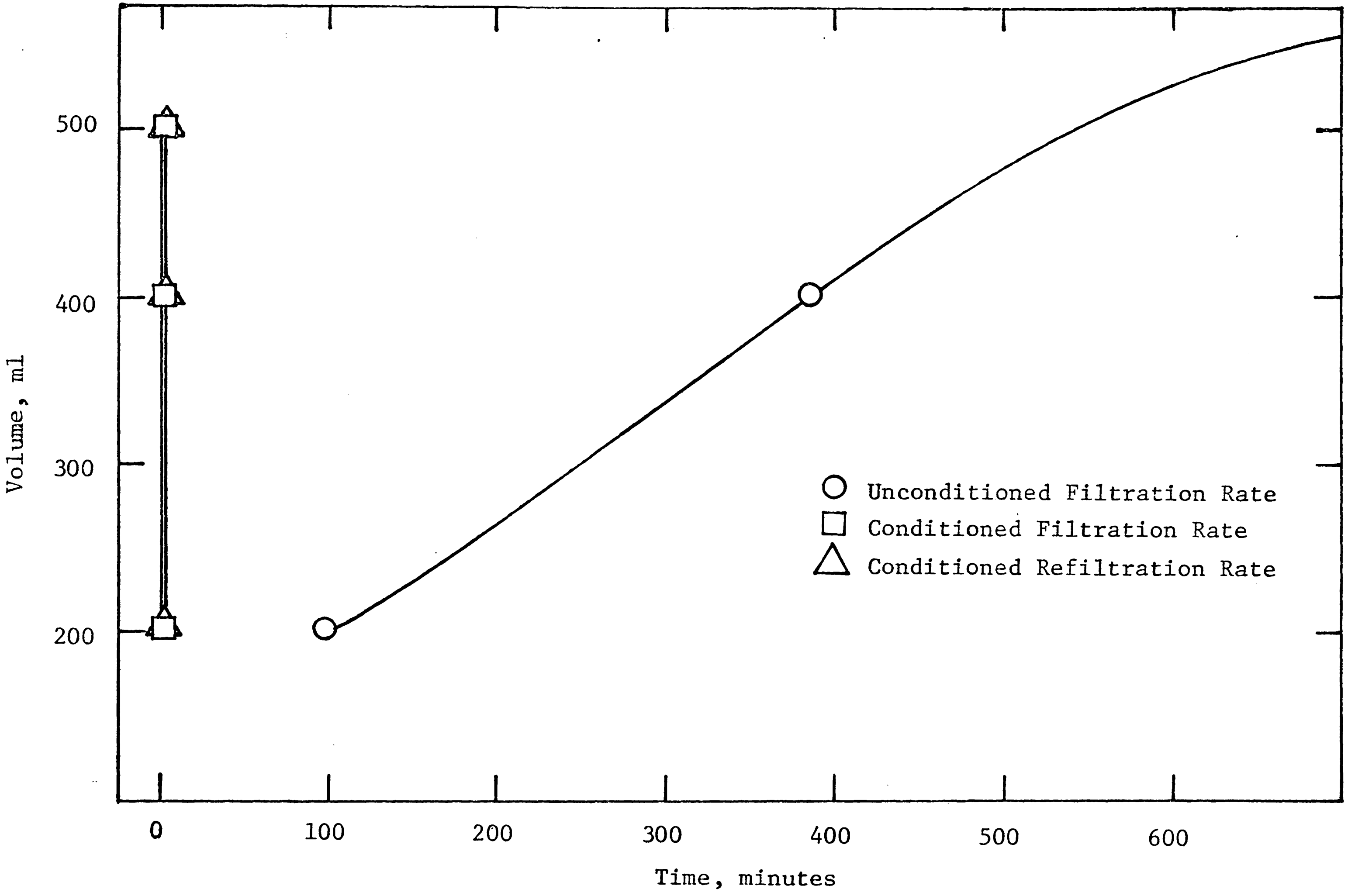

Figure 22. Comparison of Filtration Rate of Unconditioned Alum Water Treatment Sludge with Filtration and Refiltration Rates for 15 Minute Freeze Conditioned Alum Water Treatment Sludge at 3.89 Percent Suspended Solids Concentration.

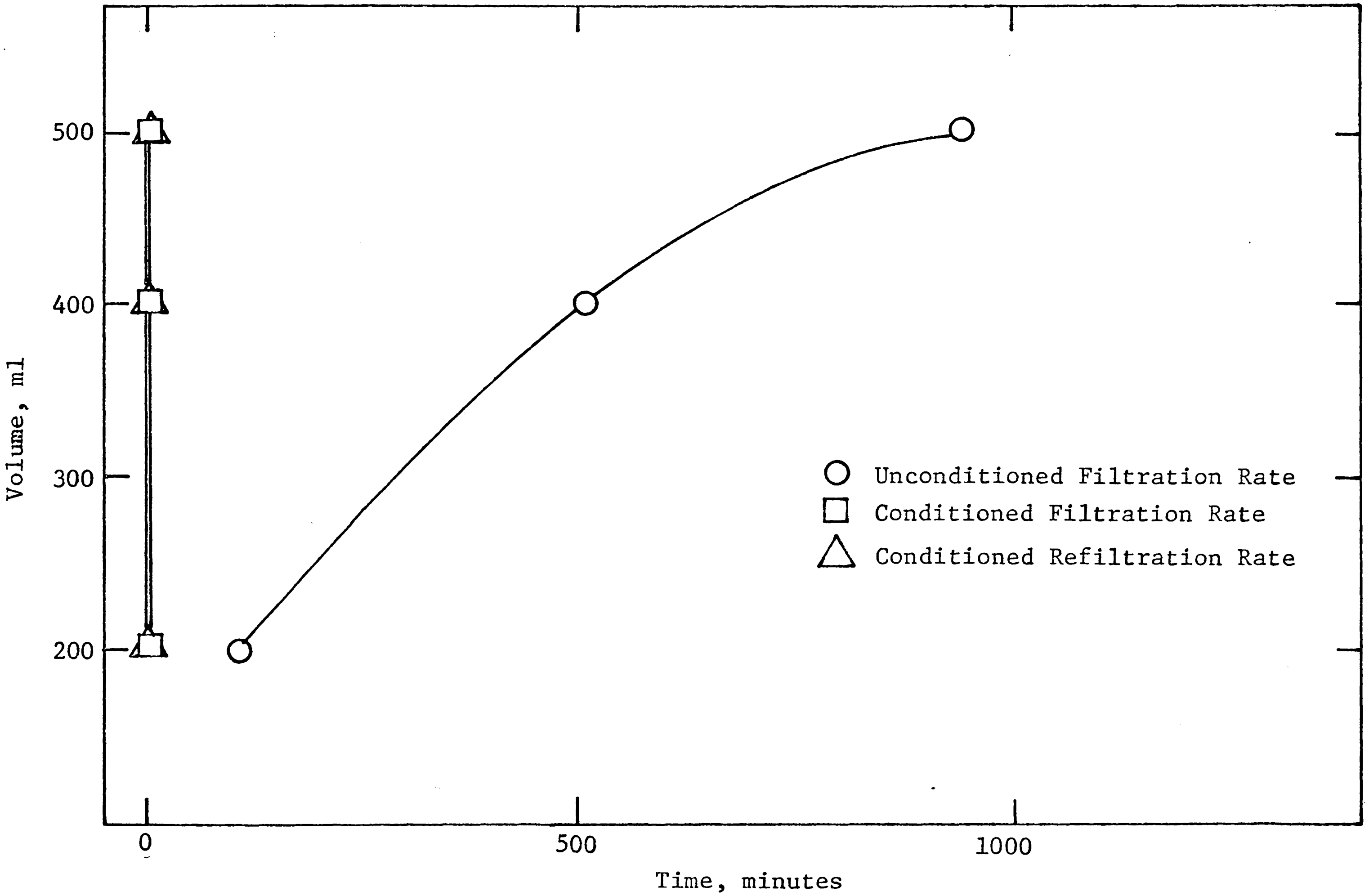

Figure 23. Comparison of Filtration Rate of Unconditioned Ferric Sulfate Water Treatment Sludge With Filtration and Refiltration Rates for 15 Minute Freeze Conditioned Ferric Sulfate Water Treatment Sludge at 3.29 Percent Suspended Solids Concentration.

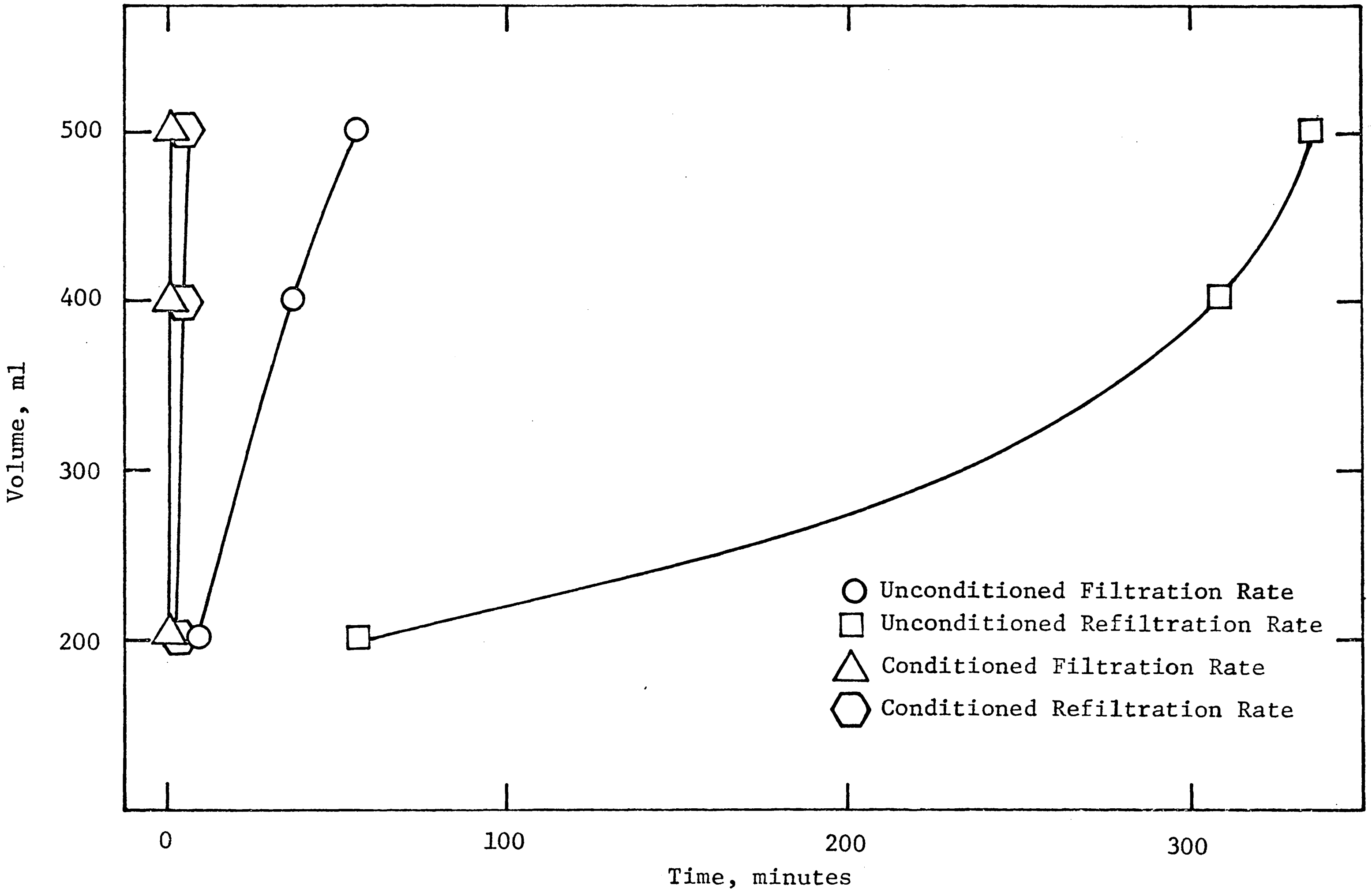

Figure 24. Comparison of Filtration and Refiltration Rates for Unconditioned and 15 Minute Freeze Conditioned Lime Advanced Wastewater Treatment Sludge at 3.32 Percent Suspended Solids Concentration.

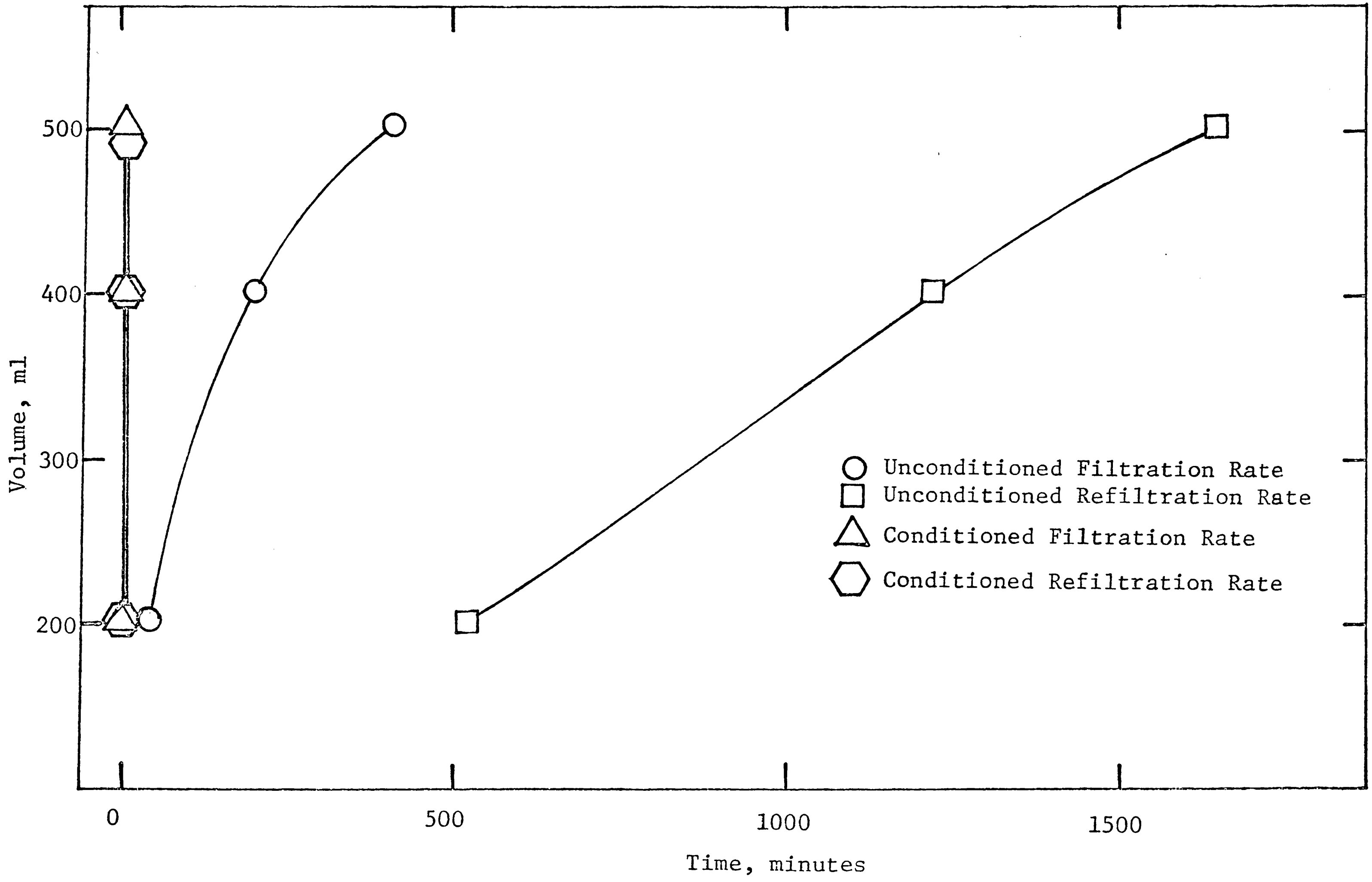

Figure 25. Comparison of Filtration and Refiltration Rates for Unconditioned and 1 Day Freeze Conditioned Ferric Sulfate Advanced Wastewater Treatment Sludge at 2.20 Percent Suspended Solids Concentration.

freeze conditioning is considered. Logsden and Edgerly (28) determined that the success of freeze conditioning is a result of particle dehydration and agglomeration. Ice crystal formation removes attached water from sludge particles causing an increase in surface tension. With increased surface tension, particles tend to agglomerate when in proximity to each other. Compression by ice crystals also takes place if the freezing rate is not slow enough to cause particle migration in front of an advancing ice interface. An increase in hydrogen ion or hydroxide ion concentration would result in either an increase of that particular ion in solution or an increase in a particular hydrolysis product of the coagulating salt, as suggested by Stumm and O'Melia (10). The former result, that is an increase in ion concentration, would probably occur with lime while increased presence of hydrolyzed metal ions could only occur with aluminum or iron coagulating salts. As long as complete freezing is allowed to occur, the physical mechanism of freezing should not be impeded by a minor pH variation. If complete freezing does not occur, the chemical and physical forces which make a sludge difficult to dewater will continue to act in binding water to solid particles.

Suspended solids were found to have an effect on the dewaterability of freeze conditioned sludges. Dewaterability of unconditioned samples as measured by the Buchner funnel specific resistance test decreased with increasing solids for ferric sulfate WT sludge and lime AWT sludge. The opposite was true for alum WT sludge and ferric sulfate AWT sludge. Coackley (31) has determined coarse particles have greater filterability than fine particles. Unconditioned lime AWT sludge and ferric sulfate WT sludge were probably composed of coarser particles than alum WT sludge or ferric sulfate AWT sludge. As stated previously, lime sludge was composed largely of the granular calcium carbonate precipitate.

Sand filtration and refiltration studies indicated that gravity rather than a substantial vacuum could not as readily dewater an unconditioned sludge. The coarseness of the lime sludge allowed for good drainability in either case. The gelatinous consistency of the remaining sludges held bound water to such an extent that gravity could not readily separate it. An increase in suspended solids for all sludges resulted in reduced gravity drainage rates. A gelatinous consistency compounded this decrease because sludge particles compacted during settling.

Freeze conditioning dehydrated and agglomerated fine particles to the extent that all conditioned samples were composed of coarse solids. All conditioned samples followed the pattern which coarse lime AWT sludge had demonstrated in the unconditioned state. An exception was the fifteen minute freeze conditioned sample of alum water treatment sludge. Investigation of specific resistance values indicated that the fifteen minute freeze conditioned sample demonstrated a tendency for those values to increase wtth increasing solids content. The one week freeze conditioned sample showed decreasing specific resistance values for increasing solids concentration. An explanation for the fifteen minute freeze conditioning results differing from the one week samples could be that either adequate cake formation time was not allowed in specific resistance testing or that the particle agglomeration process for alum WT sludge was slower than for other sludges. Inadequate cake formation was probably the reason for the reversal. At least 10 seconds was required for proper cake formation.

Sand filtration and refiltration studies of conditioned samples indicated great improvement in sample drainability. The advanced wastewater treatment sludges dewatered less readily by gravity than the water treatment sludges. Increasing solids concentration generally resulted in increased filtration times. This result indicated logically that, as sludge solids formed a cake on the sand bed, resistance to water flow was increased. Since coagulation of the advanced wastewater treatment sludges was carried to excess, large quantites of coagulant hydrolysis products of ferric sulfate and calcium carbonate and calcium hydroxide were present in the sludges. After freeze conditioning, these compounds agglomerated to such an extent that, when applied to a sand bed, a cake was quickly formed. Quick cake formation slowed the drainability of the advanced wastewater sludges over that of water treatment sludges.

Refiltration studies have the advantage of measuring filtration through a previously formed sludge cake. Refiltration times generally followed the same patterns as initial filtration. The tendency was for refiltration times to increase with increasing suspended solids concentration. As with filtration times, refiltration times were largest for the advanced wastewater treatment sludges. This result would indicate that compression of the sludge cake probably occurred in the filtration phase of sand drainage studies. The compacted cake offerred more drainage resistance than the uncompacted cake of the water treatment sludges.

From this investigation, it was determined that an inverse relationship existed between Buchner funnel specific resistance values and suspended solids concentrations while a direct relationship existed between gravity sand drainage rates and suspended solids concentrations. The basis for the latter relationship is logical. When solids concentration is increased, the resistance to water flow through the cake formed will be increased. The former relationship was reported by Gates and McDermott (35). They determined for unconditioned and polyelectrolyte conditioned alum WT sludge that an inverse linear relationship existed between specific resistance values and total solids concentrations.

Time in the frozen state has been determined by many researchers to have a major effect on dewaterability of freeze conditioned sludge (15, 17, 24, 28). Doe (17) found that freezing even fifteen minutes beyond the time required for complete freezing improved dewaterability. Rex Chainbelt, Inc. (24) determined that storage of sludge samples up to 16 hours in the frozen state significantly improved the dewatering characterisitics of the sludge sample. This investigation utilized storage times of fifteen minutes and one week to determine the effect of extended storage in the frozen state.

Results of Buchner funnel specific resistance testing indicated that lime AWT sludge and ferric sulfate WT sludge followed the tendencies noted by other researchers. Ferric sulfate AWT sludge was not tested for this parameter. Alum WT sludge possessed higher specific resistance values for one week freeze conditioned samples than for fifteen minute samples. The explanation which applied to the erratic results of suspended solids effect on specific resistance probably also applies here. Inadequate cake formation during specific resistance testing could result in the variation noted for extended storage time experiments. Results from sand drainage filtration and refiltration studies for alum WT sludge add evidence for this explanation.

Filtration studies resulted in very erratic results. Freeze conditioning dramatically changed particle consistency to the extent that gravity sand bed filtration became only a qualitative measure of the total effect of freeze conditioning. Generally, the tendency was for fifteen minute and one week freeze conditioned samples to drain at approximately the same rate or slightly faster for the one week samples.

Refiltration studies were also erratic. Alum WT sludge refiltered faster for one week freeze conditioned samples than for fifteen minute samples. This indicated that the one week freeze conditioned samples had probably agglomerated into larger particles than the fifteen minute samples. Larger particles resulted in larger pore spacing and faster drainage. This tendency did not occur with ferric sulfate WT sludge or lime AWT sludge. Results for these sludges were too erratic to draw conclusions concerning these tendencies.

From this investigation, it was determined that specific resistance values gave the best indication of the effect of extended storage in the frozen state on the dewaterability of the chemical sludges investigated. Gravity filtration and refiltration studies were hampered by the difficulty which was encountered in keeping freeze conditioned solids in suspension. Sand studies were good qualitative measures of the increased sludge dewaterability but could not be compared accurately from one sludge to another on a quantitative basis. Specific resistance values indicated that the results of this investigation compared favorably with the determination by other researchers that extended frozen storage aided dewaterability. The process of dehydration and agglomeration apparently requires time to produce best results. Dehydration is essentially complete when all water molecules have frozen. The particle agglomeration process probably requires time in excess of the fifteen minute period used in this investigation for ice pressure to force particles together.

Filtrate quality from both Buchner funnel testing and sand refiltration studies was relatively good. Suspended solids concentration was usually less than that discharged from sewage treatment plants. COD levels were not untypical of values recorded for surface waters. A pH adjustment would be required before advanced wastewater treatment effluent could be discharged.

VI. CONCLUSIONS

The results of this investigation dealing with the effect of varying operational parameters on the drainability of freeze conditioned chemical sludges support the following conclusions:

1. The freeze conditioning method has definite merit as a means of conditioning chemical water and wastewater sludges.
2. Freeze conditioning changed the physical structure of solids in chemical sludges to a granular consistency. The solids settled so rapidly that difficulty was encountered in maintaining them in suspension for specific resistance and gravity sand drainage testing.
3. Specific resistance proved to be a satisfactory parameter for quantitatively comparing the effect of freezing on different chemical sludges.
4. Gravity sand filtration and refiltration studies proved to be a satisfactory means for quantitatively measuring the effect of freeze conditioning on a particular chemical sludge and for qualitatively measuring the effect of freeze conditioning on different chemical sludges.
5. Water treatment sludges, coagulated by alum and ferric sulfate, respectively, showed the greatest improvement in dewaterability in terms of the difference between unconditioned and freeze conditioned materials. Dewatering of

wastewater sludges, coagulated by ferric sulfate and lime, respectively, was improved to a lesser extent by freeze conditioning.

6. Solids content was directly related to gravity sand filtration and refiltration rates for freeze conditioned sludges and was inversely related to specific resistance measurements for freeze conditioned chemical sludges.
7. Increased time in the frozen state resulted in improved dewaterability for all chemical sludges, as determined by specific resistance testing and gravity sand filtration and refiltration studies.

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APPENDIX

APPENDIX TABLE A-1

ALUM WATER TREATMENT PLANT SLUDGE CHARACTERIZATION

Parameter	Sample No.				
	1	2	3	4	5
Total Solids (mg/l)	38,729	40,273	43,374	46,464	49,751
Total Volatile Solids (mg/l)	8,792	9,274	10,099	11,259	11,626
Total Suspended Solids (mg/l)	35,863	38,143	38,907	42,307	44,730
Percent Volatile (%)	20.7	20.9	20.8	21.2	21.1
pH	6.2	6.2	6.2	6.2	6.2
Specific Resistance (sec^2/gm X 10^{-8})	8.42	8.80	9.85	9.83	11.45
Filtrate: Total Solids (mg/l)	326	347	383	383	370
Total Suspended Solids (mg/l)	2	3	3	4	5
COD (mg/l)	48	40	48	40	36
pH	7.3	7.3	7.3	7.3	7.3
Sand Drainage Studies					
Filtration Time to 200 ml (min)	75	61	97	105	116
Filtration Time to 400 ml (min)	296	287	385	454	498
Filtration Time to 500 ml (min)	---	---	---	---	---
Total Drainage Volume (ml)	528	529	559	562	582
Filtrate: Total Solids (mg/l)	240	241	259	242	252
Total Suspended Solids (mg/l)	9	11	9	12	10
COD (mg/l)	18	18	18	18	18
pH	7.1	7.1	7.1	7.2	7.1
Cake Moisture (%)	80	84.5	79.4	78.3	76.4

APPENDIX TABLE A-2

FERRIC SULFATE WATER TREATMENT PLANT SLUDGE CHARACTERIZATION

	Sample No.				
Parameter	1	2	3	4	5
Total Solids (mg/l)	22,342	27,734	34,298	39,150	41,612
Total Volatile Solids (mg/l)	2,931	3,749	4,834	5,083	5,427
Total Suspended Solids (mg/l)	22,077	26,647	32,917	36,690	39,853
Percent Volatile (%)	15.4	15.7	16.3	16.3	16.6
pH	7.8	7.8	7.6	7.6	7.7
Specific Resistance (sec^2/gm X 10^{-9})	1.54	1.55	1.32	1.45	1.34
Filtrate: Total Solids (mg/l)	398	482	613	610	513
Total Suspended Solids (mg/l)	9	3	4	3	4
COD (mg/l)	43	34	45	49	34
pH	8.2	8.2	8.2	8.2	8.2
Sand Drainage Studies					
Filtration Time to 200 ml (min)	29	99	103	172	190
Filtration Time to 400 ml (min)	214	435	506	807	902
Filtration Time to 500 ml (min)	363	739	937	1589	---
Total Drainage Volume (ml)	650	619	584	544	496
Filtrate: Total Solids (mg/l)	321	368	411	424	345
Total Suspended Solids (mg/l)	10	6	6	9	8
COD (mg/l)	19	19	23	26	15
pH	1.8	1.8	1.8	1.8	8.2
Cake Moisture (%)	81	77	80.8	83.5	85

APPENDIX TABLE A-3

LIME ADVANCED WASTEWATER TREATMENT SLUDGE CHARACTERIZATION

	Sample No.				
Parameter	1	2	3	4	5
Total Solids (mg/l)	24,825	30,598	35,720	44,152	55,674
Total Volatile Solids (mg/l)	4,313	5,399	6,108	7,522	9,465
Total Suspended Solids (mg/l)	23,580	28,187	33,220	42,410	53,447
Percent Volatile (%)	17,4	17,6	17.1	17.0	17.0
pH	11.8	11.9	11.9	12.0	12.1
Specific Resistance ($sec^2/gm \times 10^{-7}$)	5.84	5.67	5.67	5.49	4.51
Filtrate: Total Solids (mg/l)	496	576	633	811	939
Total Suspended Solids (mg/l)	3	4	2	2	1
COD (mg/l)	50	57	61	73	80
pH	11.6	11.7	11.7	11.9	11.9
Sand Drainage Studies					
Filtration Time to 200 ml (min)	55	64	493	375	215
Filtration Time to 400 ml (min)	1313	1215	2200	2675	2360
Filtration Time to 500 ml (min)	2326	2180	3255	4105	3615
Total Drainable Volume (ml)	724	713	663	663	652
Filtrate: Total Solids (mg/l)	436	526	---	388	437
Total Suspended Solids (mg/l)	181	247	---	65	68
COD (mg/l)	57	69	---	61	78
pH	10.8	11.0	---	11.0	11.3
Cake Moisture (%)	75.4	77.1	---	75.7	74.8
Refiltration Time to 200 ml (min)			56		
Refiltration Time to 400 ml (min)			308		
Refiltration Time to 500 ml (min)			335		
Total Drainable Volume (ml)			645		
Filtrate: Total Solids (mg/l)			524		

APPENDIX TABLE A-3 Cont'd.

Parameter	Sample No. 1	2	3	4	5
Total Suspended Solids (mg/l)			18		
COD (mg/l)			84		
pH			11.2		
Cake Moisture (%)			74.8		

APPENDIX TABLE A-4

FERRIC SULFATE ADVANCED WASTEWATER TREATMENT SLUDGE CHARACTERIZATION

	Sample No.				
Parameter	1	2	3	4	5
Total Solids (mg/l)	17,012	22,399	27,635	30,309	29,973
Total Volatile Solids (mg/l)	5,495	7,215	8,855	9,667	9,662
Total Suspended Solids (mg/l)	16,842	21,951	27,423	30,040	29,873
Percent Volatile (%)	32.3	31.8	32.0	31.9	32.2
pH	3.1	3.2	3.2	3.2	3.2
Specific Resistance ($sec^2/gm \times 10^{-8}$)	5.32	6.65	6.10	7.12	7.74
Filtrate: Total Solids (mg/l)	506	668	694	686	782
Total Suspended Solids (mg/l)	3	3	2	2	1
COD (mg/l)	--	58	112	69	73
pH	--	3.7	3.4	3.5	3.5
Sand Drainage Studies					
Filtration Time to 200 ml (min)	24	38	70	96	146
Filtration Time to 400 ml (min)	106	195	334	404	---
Filtration Time to 500 ml (min)	188	408	---	---	---
Total Drainable Volume (ml)	580	514	484	462	397
Filtrate: Total Solids (mg/l)	547	---	643	628	676
Total Suspended Solids (mg/l)	1	-	5	5	4
COD (mg/l)	58	--	35	35	35
pH	8.9	--	8.7	8.7	8.9
Cake Moisture (%)	88.1	---	89.4	91.6	93.1
Refiltration Time to 200 ml (min)		513			
Refiltration Time to 400 ml (min)		1219			
Refiltration Time to 500 ml (min)		1648			
Total Drainable Volume (ml)		526			
Filtrate: Total Solids (mg/l)		2125			

APPENDIX TABLE A-4 Cont'd.

	Sample No.				
Parameter	1	2	3	4	5
Total Suspended Solids (mg/1)		81			
COD (mg/1)		77			
pH		5.3			
Cake Moisture (%)		90.0			

APPENDIX TABLE A-5

FREEZE CONDITIONED ALUM WATER TREATMENT SLUDGE CHARACTERIZATION

	Sample No.				
	1	2	3	4	5
15 Minute Freeze					
Specific Resistance ($sec^2/gm \times 10^{-6}$)	4.16	6.11	5.44	5.47	5.55
Filtrate: Total Solids (mg/l)	358	357	366	388	390
Total Suspended Solids (mg/l)	16	7	3	8	7
COD (mg/l)	44	37	33	64	44
pH	7.1	7.1	7.1	7.1	7.2
Sand Drainage Studies					
Filtration Time to 200 ml (sec)	6	6	6	7	7
Filtration Time to 400 ml (sec)	16	14	16	18	18
Filtration Time to 500 ml (sec)	25	24	24	27	27
Total Drainage Volume (ml)	698	688	649	647	668
Filtrate: Total Solids (mg/l)	335	510	530	502	469
Total Suspended Solids (mg/l)	66	152	170	72	68
Refiltration Time to 200 ml (sec)	16	19	20	20	26
Refiltration Time to 400 ml (sec)	38	45	49	45	61
Refiltration Time to 500 ml (sec)	57	65	--	--	--
Total Drainage Volume (ml)	526	522	470	479	499
Filtrate: Total Solids (mg/l)	295	318	318	198	345
Total Suspended Solids (mg/l)	22	7	10	7	5
COD (mg/l)	37	39	41	29	37
pH	7.0	7.0	7.0	7.0	7.0
1 Week Freeze					
Specific Resistance ($sec^2/gm \times 10^{-6}$)	9.75	10.29	19.70	9.02	6.03

APPENDIX TABLE A-5 Cont'd.

	Sample No. 1	2	3	4	5
1 Week Freeze Cont'd.					
Filtrate: Total Solids (mg/l)	312	338	371	368	360
Total Suspended Solids (mg/l)	10	12	13	17	12
COD (mg/l)	56	41	49	56	45
pH	7.0	7.0	7.1	7.1	7.1
Sand Drainage Studies					
Filtration Time to 200 ml (sec)	5	6	7	6	8
Filtration Time to 400 ml (sec)	13	14	17	13	20
Filtration Time to 500 ml (sec)	22	22	26	18	31
Total Drainage Volume (ml)	678	699	683	675	681
Filtrate: Total Solids (mg/l)	401	392	345	363	276
Total Suspended Solids (mg/l)	166	126	110	138	98
Refiltration Time to 200 ml (sec)	15	11	21	17	18
Refiltration Time to 400 ml (sec)	31	26	42	34	38
Refiltration Time to 500 ml (sec)	48	37	58	47	54
Total Drainage Volume (ml)	510	529	509	501	509
Filtrate: Total Solids (mg/l)	269	295	289	301	276
Total Suspended Solids (mg/l)	16	51	5	37	23
COD (mg/l)	41	45	41	52	45
pH	7.0	7.0	7.0	7.0	7.0

APPENDIX TABLE A-6

FREEZE CONDITIONED FERRIC SULFATE WATER TREATMENT SLUDGE CHARACTERIZATION

			Sample No.		
	1	2	3	4	5
15 Minute Freeze					
Specific Resistance ($sec^2/gm \times 10^{-7}$)	1.71	3.58	3.01	2.54	1.99
Filtrate: Total Solids (mg/l)	455	505	647	561	464
Total Suspended Solids (mg/l)	29	14	13	12	13
COD (mg/l)	34	36	53	54	38
pH	8.1	8.1	8.1	8.1	8.1
Sand Drainage Studies					
Filtration Time to 200 ml (sec)	4	4	4	5	6
Filtration Time to 400 ml (sec)	9	11	12	14	15
Filtration Time to 500 ml (sec)	14	15	17	22	23
Total Drainage Volume (ml)	748	726	735	705	712
Filtrate: Total Solids (mg/l)	410	469	564	555	534
Total Suspended Solids (mg/l)	62	86	72	106	166
Refiltration Time to 200 ml (sec)	7	7	9	15	15
Refiltration Time to 400 ml (sec)	16	16	20	35	32
Refiltration Time to 500 ml (sec)	21	21	27	48	44
Total Drainage Volume (ml)	570	563	566	534	538
Filtrate: Total Solids (mg/l)	434	482	601	620	539
Total Suspended Solids (mg/l)	18	17	15	12	18
COD (mg/l)	21	26	34	30	41
pH	7.9	7.9	7.9	7.8	7.9
1 Week Freeze					
Specific Resistance ($sec^2/gm \times 10^{-7}$)	2.10	2.28	1.59	1.19	0.88

APPENDIX TABLE A-6 Cont'd.

	Sample No.				
	1	2	3	4	5
1 Week Freeze Cont'd.					
Filtrate: Total Solids (mg/l)	487	554	694	682	548
Total Suspended Solids (mg/l)	5	2	3	2	1
COD (mg/l)	41	45	59	63	57
pH	7.9	8.0	8.0	7.9	8.0
Sand Drainage Studies					
Filtration Time to 200 ml (sec)	-	6	6	5	6
Filtration Time to 400 ml (sec)	--	11	12	15	13
Filtration Time to 500 ml (sec)	--	16	18	23	24
Total Drainage Volume (ml)	715	721	716	688	699
Filtrate: Total Solids (mg/l)	838	478	666	635	618
Total Suspended Solids (mg/l)	502	106	122	86	234
Refiltration Time to 200 ml (sec)	14	10	12	15	17
Refiltration Time to 400 ml (sec)	27	22	24	32	37
Refiltration Time to 500 ml (sec)	37	29	32	44	51
Total Drainage Volume (ml)	531	557	545	515	519
Filtrate: Total Solids (mg/l)	425	433	561	585	535
Total Suspended Solids (mg/l)	35	5	5	5	14
COD (mg/l)	59	33	39	49	41
pH	8.0	8.0	7.9	7.9	7.9

APPENDIX TABLE A-7

FREEZE CONDITIONED LIME ADVANCED WASTEWATER TREATMENT SLUDGE CHARACTERIZATION

	Sample No.				
	1	2	3	4	5
15 Minute Freeze					
Specific Resistance (sec^2/gm X 10^{-6})	10.57	8.29	6.90	8.01	6.01
Filtrate: Total Solids (mg/l)	479	566	649	806	929
Total Suspended Solids (mg/l)	9	12	11	8	11
COD (mg/l)	38	47	56	68	75
pH	11.7	11.8	11.8	12.0	12.0
Sand Drainage Studies					
Filtration Time to 200 ml (sec)	8	13	10	29	20
Filtration Time to 400 ml (sec)	28	40	41	116	87
Filtration Time to 500 ml (sec)	47	63	77	202	158
Total Drainage Volume (ml)	758	708	719	703	677
Filtrate: Total Solids (mg/l)	433	604	687	635	724
Total Suspended Solids (mg/l)	162	162	202	146	113
Refiltration Time to 200 ml (sec)	61	127	114	215	214
Refiltration Time to 400 ml (sec)	146	302	279	512	539
Refiltration Time to 500 ml (sec)	307	420	393	710	---
Total Drainage Volume (ml)	572	538	552	531	493
Filtrate: Total Solids (mg/l)	252	359	443	462	560
Total Suspended Solids (mg/l)	8	16	25	15	25
COD (mg/l)	53	56	66	98	94
pH	11.1	11.3	11.4	11.5	11.5
1 Week Freeze					
Specific Resistance (sec^2/gm X 10^{-6})	10.20	9.35	8.24	5.06	4.34

APPENDIX TABLE A-7 Cont'd.

	Sample No.				
	1	2	3	4	5
1 Week Freeze Cont'd.					
Filtrate: Total Solids (mg/l)	556	580	675	886	953
Total Suspended Solids (mg/l)	4	3	3	3	3
COD (mg/l)	45	49	56	70	81
pH	11.8	11.8	11.9	12.0	12.0
Sand Drainage Studies					
Filtration Time to 200 ml (sec)	6	8	11	12	21
Filtration Time to 400 ml (sec)	29	33	61	76	116
Filtration Time to 500 ml (sec)	55	60	111	156	223
Total Drainage Volume (ml)	755	748	728	713	680
Filtrate: Total Solids (mg/l)	489	574	499	665	774
Total Suspended Solids (mg/l)	192	182	130	206	158
Refiltration Time to 200 ml (sec)	130	122	113	268	399
Refiltration Time to 400 ml (sec)	301	286	281	692	944
Refiltration Time to 500 ml (sec)	417	394	399	963	1303
Total Drainage Volume (ml)	589	581	567	546	513
Filtrate: Total Solids (mg/l)	295	389	434	568	786
Total Suspended Solids (mg/l)	7	14	10	14	7
COD (mg/l)	53	56	60	71	135
pH	11.4	11.6	11.5	11.6	11.6

APPENDIX TABLE A-8

FREEZE CONDITIONED FERRIC SULFATE ADVANCED WASTEWATER TREATMENT SLUDGE CHARACTERIZATION

	Sample No.				
	1	2	3	4	5
1 Day Freeze					
Specific Resistance ($sec^2/gm \times 10^{-7}$)	3.64	3.09	2.60	1.81	1.98
Filtrate: Total Solids (mg/l)	547	693	712	697	769
Total Suspended Solids (mg/l)	12	7	6	4	1
COD (mg/l)	58	69	73	77	81
pH	3.7	3.4	3.2	3.1	3.3
Sand Drainage Studies					
Filtration Time to 200 ml (sec)	17	24	23	24	20
Filtration Time to 400 ml (sec)	54	76	64	65	56
Filtration Time to 500 ml (sec)	84	122	93	94	83
Total Drainage Volume (ml)	719	640	712	643	640
Filtrate: Total Solids (mg/l)	575	733	841	792	739
Total Suspended Solids (mg/l)	88	100	110	104	102
Refiltration Time to 200 ml (sec)	61	96	108	113	79
Refiltration Time to 400 ml (sec)	167	269	293	312	243
Refiltration Time to 500 ml (sec)	254	---	438	---	---
Total Drainage Volume (ml)	561	482	559	486	485
Filtrate: Total Solids (mg/l)	733	920	956	1016	1034
Total Suspended Solids (mg/l)	5	4	7	8	9
COD (mg/l)	50	73	77	85	81
pH	7.8	8.1	7.7	7.9	7.7

EFFECT OF VARYING OPERATIONAL PARAMETERS ON THE DRAINABILITY OF FREEZE CONDITIONED CHEMICAL SLUDGES

by

Larry Michael Simmons

(ABSTRACT)

Tests were run on samples of four chemical sludges including two water treatment sludges resulting from coagulation by alum and ferric sulfate, respectively, and two advanced wastewater treatment sludges, resulting from coagulation with ferric sulfate and lime, respectively. The purpose of the testing was to determine the effect of freeze conditioning on the drainability of the chemical sludges and to evaluate operational parameters affecting optimum drainability by freeze conditioning. Specific resistance testing and gravity sand filtration and refiltration studies were used to determine the drainability of unconditioned and freeze conditioned samples. Unconditioned sludge was characterized by testing for total and total suspended solids, total volatile and total volatile suspended solids, and pH.

Results indicated that freeze conditioning dramatically improved drainability of all chemical sludges investigated. Conditioned samples exhibited a granular consistency which settled rapidly. Specific resistance testing indicated that values obtained varied inversely with solids content for freeze conditioned samples. A direct relationship existed between filtration and refiltration rates and solids

content for freeze conditioned samples. It was also determined that with increased storage time in the frozen state, drainability of the chemical sludges increased, as measured by specific resistance testing and gravity sand drainage studies. Filtrate quality of freeze conditioned samples was comparable to the quality of wastewater secondary effluent and some surface waters.